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History of Magnetorheological Finishing

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With contributions from William Kordonski, Don Golini, Lowell Mintz, Steve Jacobs, Paul Dumas, Greg Forbes, Steve Hogan, and Carolyn Russell (née Policove)

ABSTRACT

Magnetorheological finishing (MRF) is a deterministic method for producing complex optics with figure accuracy <50 nm and surface roughness <1 nm. MRF was invented at the Luikov Institute of Heat and Mass Transfer in Minsk, Belarus in the late 1980s by a team led by William Kordonski. When the Soviet Union opened up, New York businessman Lowell Mintz was invited to Minsk in 1990 to explore possibilities for technology transfer. Mintz was told of the potential for MRF, but did not understand whether it had value. Mintz was referred to Harvey Pollicove at the Center for Optics Manufacturing of the University of Rochester. As a result of their conversation, they sent Prof. Steve Jacobs to visit Minsk and evaluate MRF. From Jacobs' positive findings, and with support from Lowell Mintz, Kordonski and his colleagues were invited in 1993 to work at the Center for Optics Manufacturing with Jacobs and Don Golini to refine MRF technology. A "preprototype" finishing machine was operating by 1994. Prof. Greg Forbes and doctoral student Paul Dumas developed algorithms for deterministic control of MRF. In 1996, Golini recognized the commercial potential of MRF, secured investment capital from Lowell Mintz, and founded QED Technologies. The first commercial MRF machine was unveiled in 1998. It was followed by more advanced models and by groundbreaking subaperture stitching interferometers for metrology. In 2006, QED was acquired by and became a division of Cabot Microelectronics. This paper recounts the history of the development of MRF and the founding of QED Technologies.

IT BEGAN IN MINSK WITH WILLIAM KORDONSKI

Appearing at the end of a mathematical proof, *QED—quod erat demonstrandum*—is Latin for "what was to be demonstrated." In the world of optical finishing QED Technologies is the name of an American company that reduced to practice the art of magnetorheological finishing (MRF). The story of this revolutionary technology illustrates the vision, entrepreneurial drive, and trust among the people who turned a dream into reality.

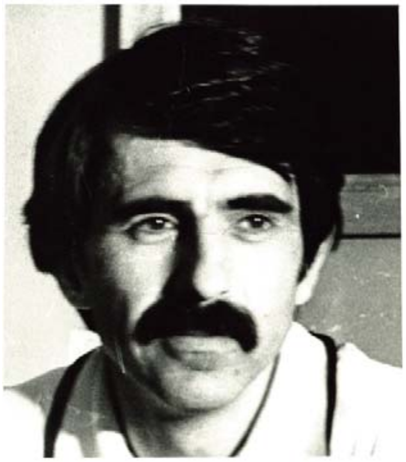

Figure 1. William I. Kordonski (1938–). Inventor of MRF. 1982 photo.

The tale begins in the Soviet Union. William Kordonski (Figure 1) was born in a small town near Vinic, Ukraine in 1938 and graduated from the State Maritime University in Odessa in 1961 with a degree in mechanical engineering. He worked in the aviation industry near Moscow until enrolling in a graduate program (called the *aspirantura* in the Soviet Union) in 1968. William earned his PhD in 1971 at the Heat and Mass Transfer Institute of the Byelorussian Academy of Science in Minsk, which is the capital of post-Soviet Belarus. His dissertation entitled "Mass Transfer and Hydrodynamics of the Disk Rotating in Non-Newtonian Fluids" was conducted under the guidance of Prof. Z. P. Shulman and Academician A. V. Luikov, whose name the Institute now carries. William remained at the Institute as a research scientist, senior research scientist, and then a head of laboratory for another 25 years.

In 1974, William started work on *magnetorheological (MR) fluids*, which are suspensions of micron-size ferromagnetic particles, such as iron, in fluids such

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as oil or water. The viscosity of the fluid increases in the presence of a magnetic field. The stronger the field, the stiffer the fluid becomes. A *ferrofluid* is a suspension of smaller (submicron colloidal) magnetic particles. The increase in viscosity in the presence of a magnetic field—called the *magnetoviscous effect*—is much less for a ferrofluid than for a magnetorheological fluid. The ability of either kind of fluid to transmit force can be controlled by the strength of the applied magnetic field. Both types of fluids are candidates for use in actuating or damping mechanical motion. Each particle in a ferrofluid consists of a single magnetic domain. Each particle in a magnetorheological fluid has multiple magnetic domains. Particles in the magnetorheological fluid acquire much stronger magnetic moments than do particles in a ferrofluid.

Initial interest was in using "smart" MR fluids for mechanical applications such as vibrational damping and actuators (Figure 2). The main challenge was to create stable MR fluid suspensions, rather than thick, paste-like mixtures of solids and liquids which were characteristic of the state of the art. William Kordonski and two or three people working with him developed a stable MR fluid and built the first magnetorheometer to measure mechanical properties of MR fluids in a magnetic field. Fundamental studies of the magnetorheological effect were accompanied by building prototype magnetorheological devices. In 1982, William co-authored the first book on the *Magnetorheological Effect* with Z. P. Shulman, discussing both theory and applications. The book became part of William's thesis for his Doctor of Science degree, which was awarded by the State Scientific Research Institute of Chemical Products, Kazan, Russia, in 1985. Doctor of Science in the Soviet Union was a higher level degree than the Ph.D. and was earned by about 4% of those with a Ph.D.

Figure 2. Prototype robot in 1986 uses MR fluid actuators. *Left to right:* Svetlana Demchuk, William Kordonski, Nikolai Protacevich.

In 1986, Kordonski attended a symposium in which he learned that aspheric optics were required for surveillance by spacecraft, but that methods to make such optics were not well developed. In 1986 or 1987, William met Leonid Gleb, a group leader working on new technologies for optics fabrication at the 20,000-person Byelorussian Optical Mechanical Organization in Minsk. Gleb was investigating a polishing method employing abrasive particles and a pad suspended in a ferrofluid.[1,2] William suggested using a magnetorheological fluid, rather than a ferrofluid. The stiffened MR fluid would replace the polishing pad. Gleb was receptive and the two began a collaboration. Prior to and concurrent with the work in Minsk, research was underway in Japan to use ferrofluids for polishing.[3,4,5,6,7]

By 1990, William's group had an operating magnetorheological finishing (MRF) machine in Minsk. The machine shown in Figures 3 and 4 features a shallow, nonmagnetic, electrically insulating, cylindrical trough containing MR fluid and polishing abrasive. North and south pole pieces from an electromagnet straddle the trough. A workpiece such as a ground glass lens is held on a rotating spindle. The trough rotates at 60 revolutions per minute (rpm). The spindle holding the workpiece spins at 700 rpm and can be tipped from vertical to 25° off vertical. MR fluid in the rotating trough stiffens by a factor of 100 when it enters the ~4 kilogauss magnetic field near the workpiece. The stiffened fluid conforms to the shape of the workpiece.

Two key features of the MR polishing process are that the lap conforms to the shape of the workpiece and only part of the workpiece contacts the fluid at any moment. Removing material from just one region at a time, rather than the entire surface, is called *subaperture polishing*. The amount by which an optical component deviates from its design value is called the *optical figure*. By polishing different regions for different amounts of time, subaperture polishing can provide figure correction. In an ideal process, a surface map of the part is constructed prior to polishing. Then material is removed from the high points by computer-controlled polishing to correct the shape. After each cycle, a new map is made and polishing is repeated for further figure correction. Ideally, successive polishing cycles make the surface smoother and improve the optical figure. The Minsk group did not know what the shape of the polishing zone was, so they were hindered in their ability to deterministically change the surface shape;.

Figure 3. William Kordonski in Minsk in 1992 with his first magnetorheological finishing (MRF) machine.

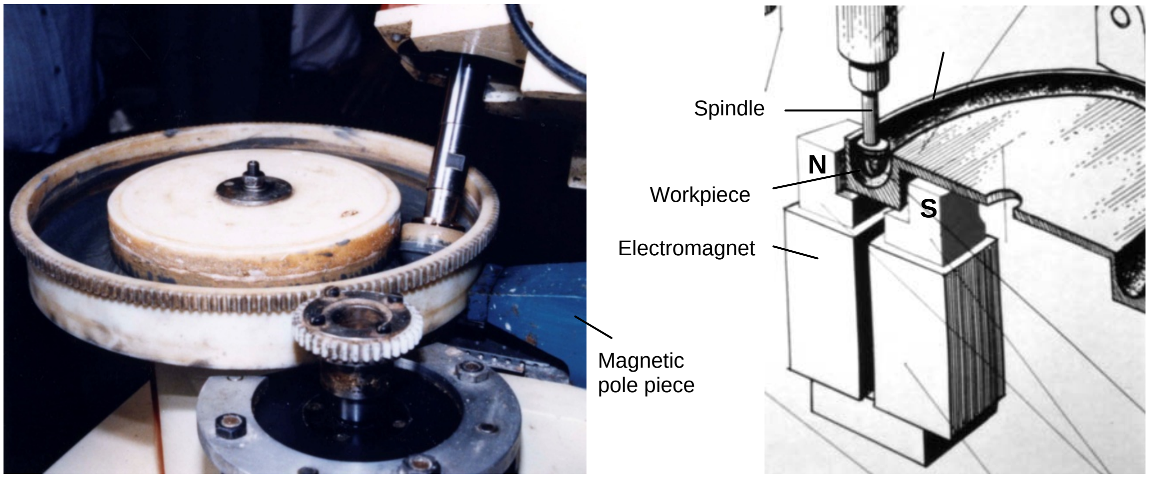


Figure 4. Close up photo and diagram of MRF machine in Minsk in 1992.

By 1992, work at Minsk had demonstrated that magnetorheological finishing is possible. But what steps could be taken to make it practical? To little avail, William talked to people from the Soviet/Russian optical industry, including leadership, in an attempt to move technology to a higher level. The restructuring of the Soviet economic and political system, called *perestroika*, under Premier Mikhail Gorbachev in the late 1980s opened the Soviet Union to contact with the outside world. William traveled to international conferences. He made his first trip to the United States for a conference on electrorheological fluids at Southern Illinois University in 1989. He attended a conference on smart materials in San Diego in 1990. He discussed ideas for MRF development with Americans, Germans, Dutch, and South Koreans, but nobody was adventurous enough to come forward with investment capital until William met Lowell Mintz.

ENTER LOWELL MINTZ

Figure 5. Lowell Mintz (1938-) in 1999.

Lowell Mintz (Figure 5) was born in Brooklyn, New York in 1938 and raised in Florida. He graduated from Rollins College in Florida with a BA in philosophy in 1959. Lowell made his fortune as a broker on the commodity futures exchange in New York, specializing in copper, silver, and gold. He served as Chairman of the Commodity Exchange from 1979–1981. When his term ended, Lowell began looking for something new to do and ended up in business ventures with his friend Paul Williamson who had been in the Air Force Reserve with Lowell twenty years earlier.

When the Soviet Union opened up in 1989, the Academy of Sciences in Minsk sought to build a center for international meetings on heat and mass transfer. William Begell was a US publisher of scientific journals from Russia. He was asked by the Academy of Sciences to help find a developer to build the new conference center. Begell approached Williamson and Mintz about the project. Soon, scientists from Minsk were asking Williamson and Mintz to visit Minsk so they would understand the work being conducted there. In 1990, Mintz, Williamson, and their partner Dave DeBusschere (a former New York Knicks basketball player) travelled to Minsk to meet with the Academy of Sciences and to discuss real estate development.

To their surprise upon their arrival, they were asked to meet with the Prime Minister of the Republic of Byelorussia. Mintz's party was among the first Western businessmen to come to the Soviet Union during *peristroika* and the government was eager to explore commercial opportunities with the West. Therefore, Lowell began to look for potential business opportunities during his visit. As a self-described "gadgeteer interested in how things worked," Lowell felt "like a kid in a candy store " during his grand tour of the Heat and Mass Transfer Institute. Among the projects he saw, William Kordonski's magnetorheological fluids made a strong impression. William explained the potential for using MR fluids in shock absorbers and robotic arms, and for "polishing aspheres."

Mintz and his partners formed a company, Byelocorp, in 1991 to conduct business with Byelorussia. In 1992 Mintz formed Byelocorp Scientific, Inc. (BSI) specifically for technology transfer. William Kordonski and his associates had formed a company called MART (Magnetorheological Technologies) to commercialize their technology. BSI, MART, and the Heat and Mass Transfer Institute signed a contract giving BSI rights to MART's magnetorheological fluid technology. BSI would fund the Minsk group and had exclusive rights to anything that would be developed.

In considering applications for magnetorheological fluids, Mintz concluded that it would be too difficult and expensive to enter markets for shock absorbers and robotic arms. As for "aspheres," Lowell did not even know what they were! He had to ask a friend for an explanation. Lowell learned that there was real potential for aspheric lenses, but he "hadn't the slightest idea" of whether magnetorheological fluid polishing could be used to make aspheres. Lowell consulted with his college fraternity brother, William Dunnill, who was head of the optics company, Leica Technologies. Dunnill referred Lowell to Robert Fischer of the optical design company, Optics 1. Fischer, in turn, recommended that Lowell talk to Harvey Pollicove at the newly formed Center for Optics Manufacturing in Rochester, New York.

HARVEY POLLICOVE AND THE CENTER FOR OPTICS MANUFACTURING

Harvey Pollicove (Figure 6) was born in Utica, New York in 1944. He started college in Utica, but was asked to leave because of poor performance. Harvey took a job around 1966 at Eastman Kodak in Rochester, New York as a lens grinder. In a most fortunate turn of history, a master artisan at Kodak told Harvey that he needed to go back to school because he was never going to be a good optician. Harvey took this advice and enrolled in the University of Rochester where he earned a degree in mathematics in 1973. Returning to Kodak, Harvey worked in optics manufacturing, production engineering, and technical market sales. In the 1970s, Harvey led a team to develop a lens fabrication process that enabled the creation of the disk camera. Later, he led a project to improve the optics for compact disk players. In the 1980s, Harvey headed Kodak's optics manufacturing in Asia.

Figure 6. Harvey Pollicove (1944-2004) conducting a tour of COM.

Pollicove realized from his Asian experience that the U.S. needed to automate optics manufacturing to remain competitive. He took advantage of Kodak's "executive loan" program to go to the University of Rochester in 1988-1990 to explore the possibility of forming a Center for Optics Manufacturing (COM) to help automate the U.S. optics industry.[8] That industry consisted of many companies that were too small to conduct their own research and development and a few large companies whose research and development was proprietary. Harvey's vision was to create a consortium of industry and academia—with significant government support—to develop automated manufacturing technology that would be commercialized and available to industry. His motto was "industry implementation is the only hallmark of success."

Harvey retired from Kodak in 1990 to join the University of Rochester and to become the director of COM. Duncan Moore, Professor of Optics at the University of Rochester was co-founder of COM. Principal members were the University of Rochester, the University of Central Florida, the University of Arizona, and the American Precision Optics Manufacturing Association. Significant manufacturing technology financial support was obtained from the U.S. Army Materiel Command through Stanley Kopacz at Picatinny Arsenal. In 1992, construction began on a 96,000 square foot home for COM.

The first major thrust at COM was in computer numerically controlled (CNC) deterministic grinding of optics, which led to a line of grinding machines called OPTICAM (which stands for OPTICs Automation and Management).[9] By 1992, the prototype OPTICAM machine could manufacture optics with root-mean-square roughness in the range 10–30 nm, a peak-to-valley surface figure of <1 wavelength, and 1–2 microns of subsurface damage. Concurrently, the Center fostered the advance of manufacturing process science and technology and established training and education for the optics industry.[10,11] Don Golini joined COM in 1992 to manage the manufacturing science program, which included seventeen faculty and more than 20 graduate students.

With the commercialization of OPTICAM for efficient, deterministic grinding, the next challenge was deterministic polishing. But what technology could provide deterministic polishing?

OPPORTUNITY KNOCKS

Around April 1992, Lowell Mintz, William Kordonski, and Lowell's associate, William Begell, visited Harvey Pollicove to introduce him to magnetorheological finishing. Begell was Director of Science Development for Byelocorp Scientific and his role also included helping Kordonski with English. Mintz and Kordonski were bound by orders from their attorney that no technical information could be divulged without compromising a patent application. Pollicove's position did not allow him to sign a confidentiality agreement. Policove kept asking questions that Mintz and Kordonski were not allowed to answer. Mintz and Kordonski then pulled out of their pockets glass aspheres that they had been carrying around. Exasperated, Harvey exclaimed "I finally understand this. You have a black box and you put in an unfinished part and it comes out an asphere!"

Harvey looked at the aspheric lenses, which were quite scratched from the way they had been carried around. He went to the lab and inspected a lens with an interferometer. He observed "a scratched lens with a couple of beautifully polished spots," according to Mintz. William Kordonski was amazed by the modern optical metrology available at COM. The group went back to Harvey's office trying to figure out how they could discuss magnetorheological finishing without jeopardizing their patent application. Just at that moment, Steve Jacobs walked past the door, and Harvey exclaimed “I can’t sign a confidentiality agreement, but Steve can!” According to Steve, “Harvey dragged me in … and asked me to listen to their pitch.” William showed a lens to Steve, who was incredulous that it could have been polished by sticking the lens into a magnetic fluid. William showed pictures of the polishing apparatus to Steve, but he still “did not believe that the lens could have been polished that way.”

THE JACOBS REPORT 1992

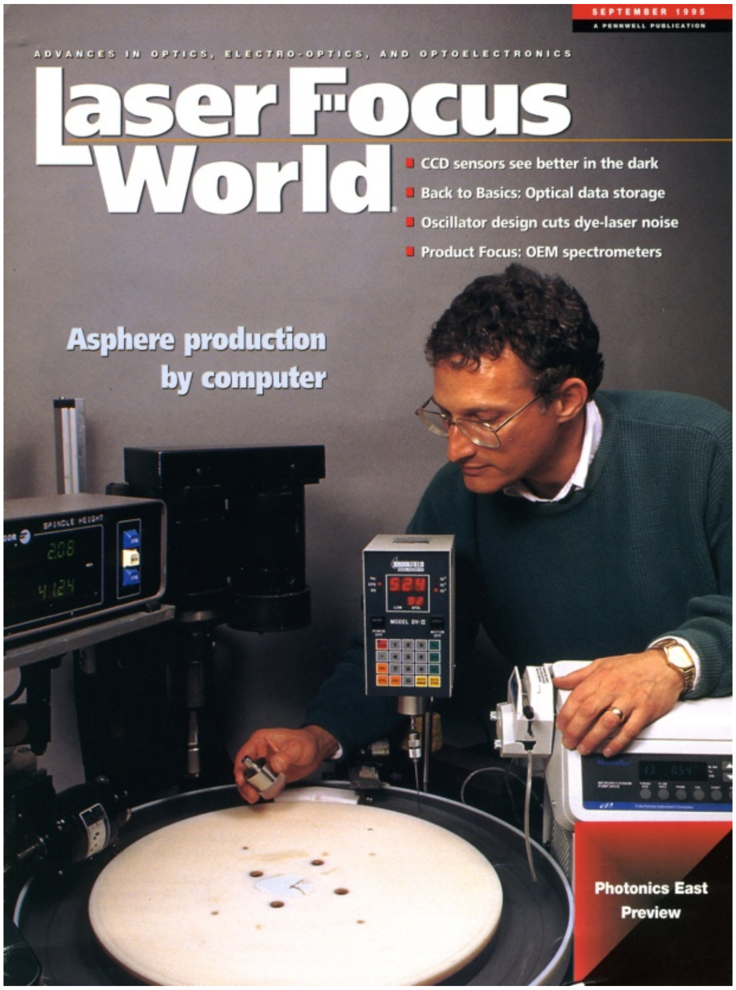


Figure 7. Steve Jacobs and the “preprototype” MRF trough machine at COM were featured on the cover of *Laser Focus World* in September 1995.

Steve Jacobs was born in Denver in 1948. He earned a BS in Optics at the University of Rochester in 1970 and a PhD in Optics from the University of Rochester in 1975. He stayed on as a postdoc in the Laboratory for Laser Energetics, where he became a member of the technical staff and, later, Senior Scientist. In 1988, Steve became Associate Professor in the Institute of Optics at the University of Rochester and in 2000 he was promoted to Professor in the Institute of Optics and in the Department of Chemical Engineering. The following year, he became Professor in the Materials Science Program. In 2010, Steve remains Professor thrice over and heads the Optical Materials Technology Department in the Laboratory for Laser Energetics.

It was a fateful day in April 1992 when Steve Jacobs walked past the doorway where Harvey Pollicove was frustrated by his visitors’ inability to share any details of magnetorheological finishing. Steve did not believe the method could possibly work. Lowell Mintz asked Steve to go to Minsk and observe the process for himself. Lowell obtained a visa and a ticket for Steve to visit Minsk in August 1992. Jacobs visited the Institute of Heat and Mass Transfer, met the people, and witnessed an experiment in which a ground glass lens on a spindle was dipped into a trough with a magnetic fluid. “There was some kind of program to move the lens through various angles. Sure enough, it came out polished!”

Steve Jacobs’ heavily illustrated nine-page report dated 16 October 1992 is a gem for being clear, brief, and complete.[12] Figures 3 and 4 show what Steve saw in Minsk. “The polishing process is best understood by thinking of the MR fluid as the lap…. Its shape and stiffness can be controlled in real time…it is aqueous…and a small amount is adequate for polishing a large number of parts…. Material removal occurs when a spindle-mounted glass part is rotated against the polishing slurry, which is also in motion. Both the magnitude and form of the pressure applied through the abrasive particles to the part are controlled by a magnetic field…. Removal rates are about 0.5 to 1.0 μm per minute, but much can be done here… A computer program is used to calculate the correct dwell time for the part against the slurry for each of several contact angles. One polishing cycle, which consists of contact polishing for about one minute at each of 14 separate angles, is repeated several times to polish out the part.” Figure 8 shows the improvement in shape of one of nine glass lenses polished during Jacobs’ visit. The report concludes with a

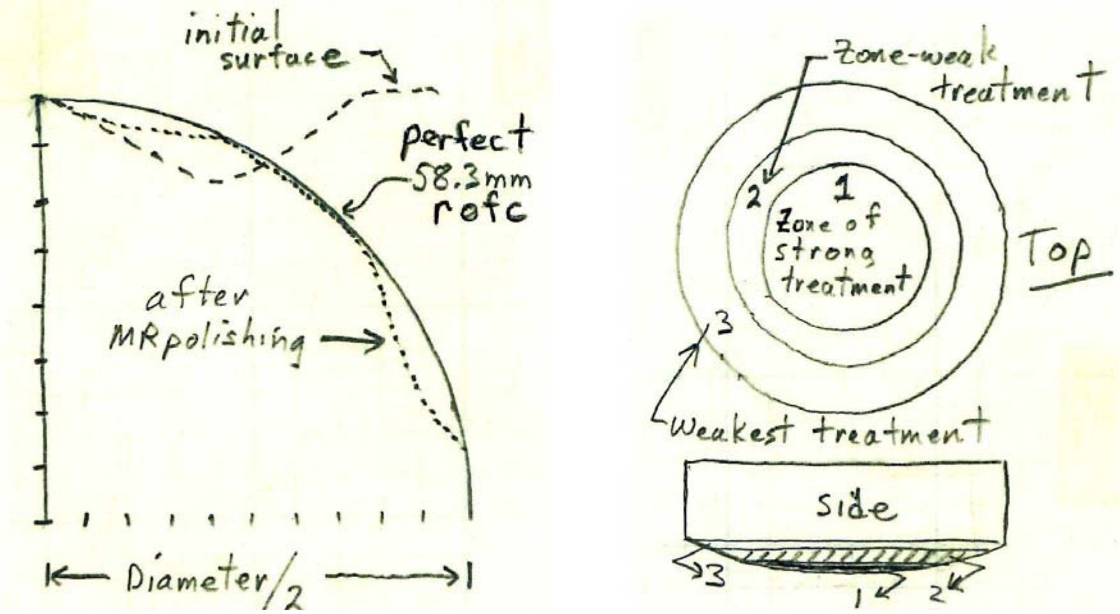


Figure 8. *Left:* Improvement in optical figure of 40-mm-diameter glass lens before and after 30 cycles (7.5 hours) of MR polishing in Minsk in 1992. *Right:* Diagram showing polishing zones observed when convex lens was dipped into MR fluid at normal incidence to the lens. Drawings from Jacobs' report, reference 12.

modification proposed by the Minsk group to increase the polishing rate for convex lenses with diameters from 10 to 80 mm. The report was protected with the statement "patent pending with rights assigned to Byelocorp Scientific, Inc."

Following the Jacobs visit to Minsk, William Kordonski presented a paper at the Optical Fabrication and Testing Workshop in Boston in November 1992 showing that magnetorheological fluid was capable of polishing glass, zinc selenide, gallium arsenide, sapphire, quartz, and silicon nitride.[13] The material removal rate for glass had a sigmoidal dependence on magnetic field intensity shown in Figure 9. Figure 10 shows a chain of spherical magnetic iron particles formed along the magnetic lines of force in the MR fluid. Larger angular particles of alumina abrasive cling to the magnetic chain.

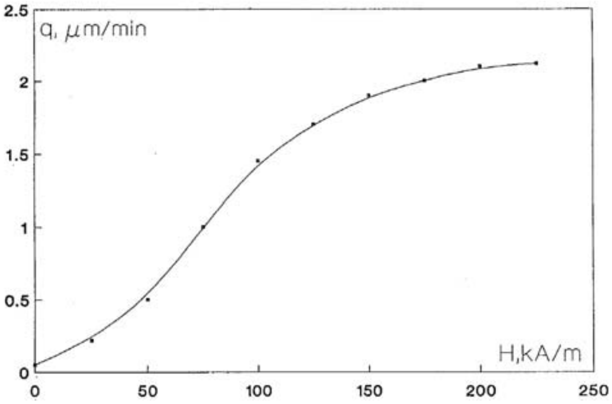


Figure 9. Dependence of removal rate (q, μm/min) on magnetic field intensity, H, near the surface of the TF-10 glass workpiece.[13]

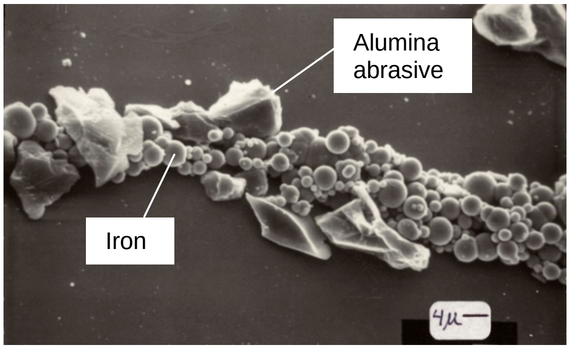


Figure 10. Chain of circular iron particles in MR fluid aligned along magnetic lines of force. Larger, angular particles adhering to the chain are grains of alumina abrasive.[13]

MRF AT COM

After the 1992 meeting of Lowell Mintz and Harvey Pollicove, but before Steve Jacobs visited Minsk, Byelocorp Scientific (BSI) signed a technology agreement with MART and the Luikov Institute of Heat and Mass Transfer on 6 June 1992 for MART to conduct research of mutual interest. BSI would obtain patents and was responsible for promotion, marketing, and sales of the technology. The first U.S. patent for MRF polishing was filed by BSI on behalf of MART in June 1993.[14]

On the basis of the Jacobs report, and with difficulty, a project agreement was signed on 12 January 1993 between BSI and the University of Rochester "to optimize the magnetorheological optical finishing process developed by MART scientists." BSI would provide funds to COM to host scientists from Minsk. Steve Jacobs and Don Golini at COM would work with the visiting scientists to replicate what was achieved in Minsk and then advance the technology to practical application. Now there was a path forward for MRF deterministic polishing to complement OPTICAM deterministic grinding. Harvey Pollicove's interest in MRF technology was a key factor in its development.

Figure 11. Don Golini (1964–) in 2000.)

Don Golini (Figure 11) was born in 1964 and raised in Everett, Massachusetts. After earning a BS in Optics from the University of Rochester in 1986, he returned to Boston to work for Itek Optical Systems in Lexington, Massachusetts manufacturing large mirrors. While at Itek, Don earned an MS in Electro Optics from Tufts University in 1990 for his studies of the physics of loose abrasive grinding with Steve Jacobs in Rochester. In 1992, Golini was recruited to join COM to manage the manufacturing science program.

William Kordonski arrived in the U.S. in the spring of 1993 to work for 6 months to build prototype magnetorheological equipment (Figure 12). He assisted a group at Virginia Tech on mechanical applications of MR fluids and he worked with COM to replicate the Minsk optical finishing machine. Gennady Gorodkin and Alina Matsepuro also came from Minsk to work at COM. Gorodkin assembled hardware and Matsepuro prepared the magnetorheological fluid. Birgit Puchebner (now Gillman) of the Jacobs group carried out a host of experiments on the MR fluid. Magnets provided from Minsk enabled Mike Bechtold of CNC Systems, Ontario, New York to build the "preprototype" polishing machine in just eight weeks. CNC Systems later became OptiPro Systems.

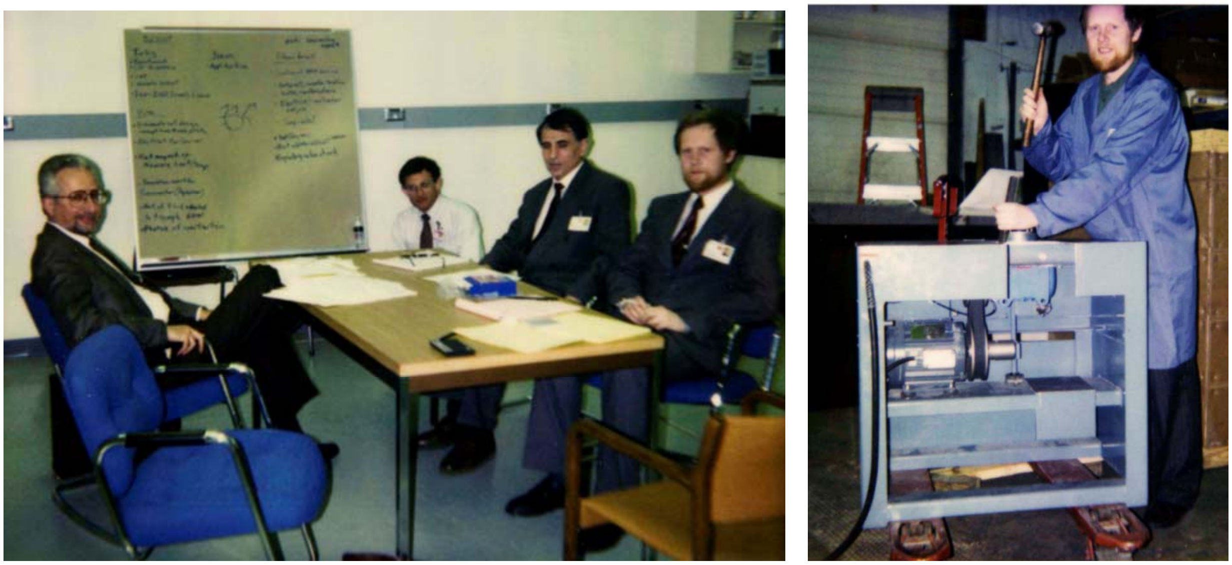


Figure 12. *Left:* Lowell Mintz (left), Steve Jacobs, William Kordonski, and Gennady Gorodkin confer on 31 March 1993 at COM. *Right:* Gorodkin at CNC Systems on 1 April 1993 beginning assembly of MRF hardware.

Initial polishing trials were conducted by Gennady Gorodkin in early June 1993 with the machine shown in Figures 13 and 14. To everyone's delight, significant polishing action was immediately observed. However, visitors to COM from the optics industry in the summer of 1993 were quite skeptical about the practical utility of magnetorheological finishing.

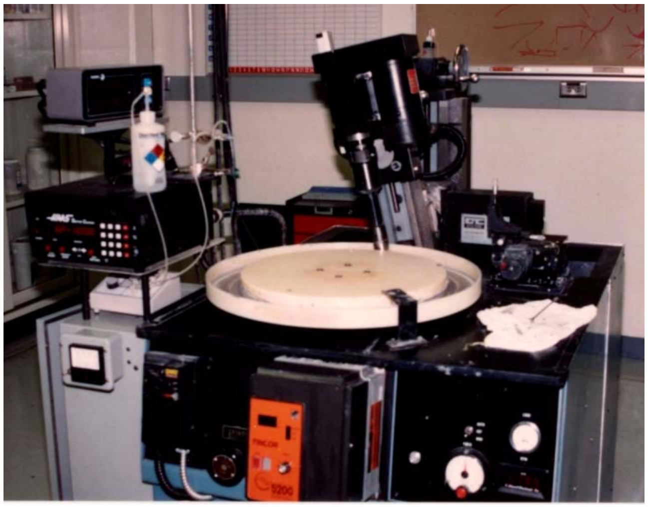


Figure 13. "Preprototype" trough MRF machine operating at COM in 1993. The trough was rotated at 40 rpm and the spindle was rotated at 200 rpm.

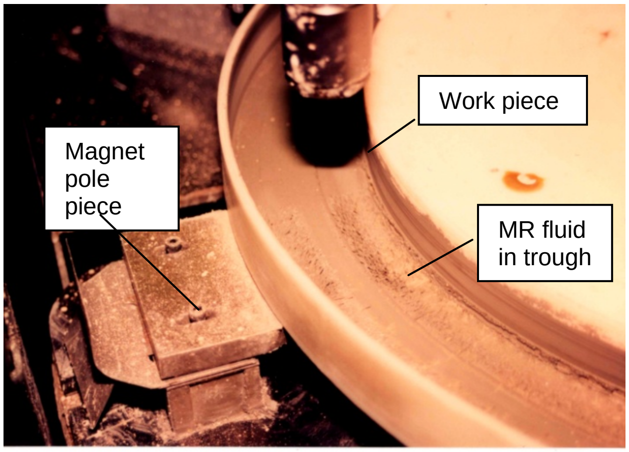


Figure 14. View of one of two magnetic pole pieces. The second pole piece is underneath the turntable inboard of the trough.

The "preprototype" MRF trough machine in Figure 13 had the same two degrees of freedom as the Minsk machine in Figures 3 and 4. The spindle in Figure 15 was tilted around the **B** axis by computer control to polish successive annular regions of the convex workpiece. A manual setup adjusted the **B** axis to be coincident with the center of curvature of the workpiece. The spindle could be raised and lowered manually along the vertical **Z** axis to control the depth of immersion in the fluid.

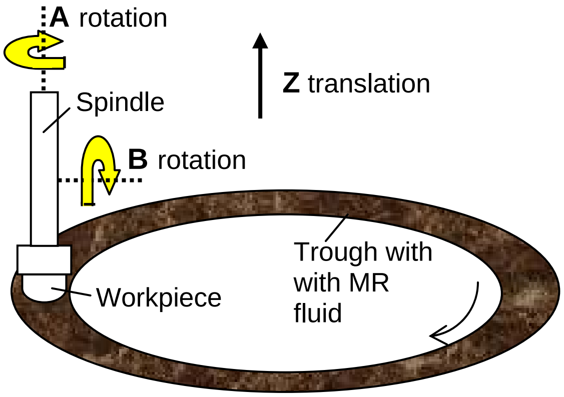


Figure 15. Coordinate system showing two degrees of freedom of the first MRF trough system set up at COM in 1993. The trough and spindle each rotate at a constant rate, so rotation of the spindle about the **A** axis is not a variable. The two degrees of freedom are tipping of the spindle (rotation around the **B** axis) and translating the spindle manually along the **Z** axis.

THE FORBES-DUMAS CODE

It had now been shown that the Minsk MRF machine and its capabilities could be replicated at COM. The next step was to gain deterministic control of the process. When a glass workpiece is briefly immersed in the rotating trough and held stationary, a D-shaped “spot” is polished into the glass (Figure 16). The spot is also called the “footprint” or the “removal function.” The depth of material removal at the straight edge of the D is about twice as great as the depth of removal at the curved front. How could this material removal pattern be employed to achieve a desired optical figure on a lens? Professor Greg Forbes and his student Paul Dumas tackled this problem in 1994.

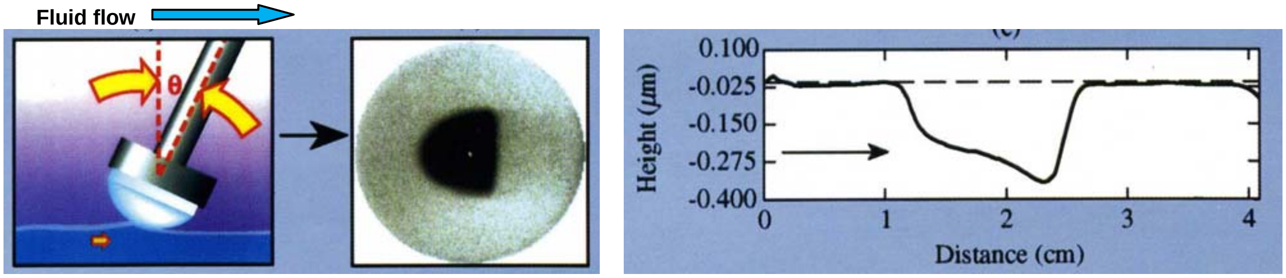


Figure 16. Polishing spot observed when stationary glass workpiece is held in rotating MRF trough for 5 s.[15]

Greg Forbes (Figure 17) was born in Brisbane, Australia in 1959 and attended high school in Melbourne. He thought he would follow his father’s footsteps into engineering, but discovered a love for theoretical physics at the University of Sydney, where he earned a BS in mathematics and honors in theoretical physics in 1980. He received a Ph.D. from the Australian National University in Canberra in theoretical physics in 1984 working on Hamiltonian optics. Greg won a Fulbright Scholarship to come to the Optical Science Center at the University of Arizona where he worked with Bob Shannon, Roland Shack, and Jim Wyant. In 1984, Duncan Moore (later a co-founder of COM) offered Forbes a faculty position at the University of Rochester. Forbes’ visa status required that he first return to Australia, so he did not take up residence in Rochester until 1985.

Figure 17. Greg Forbes (1959–) is the applied mathematician on the MRF team. Photo from 1999.

Figure 18. Paul Dumas (1968–) is the software developer for MRF. Photo from 2004.

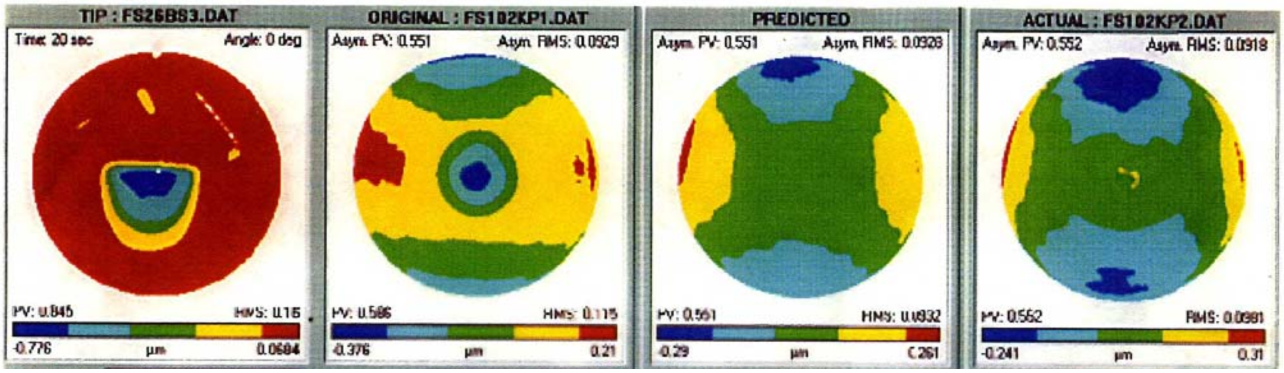
While attempts were made to create a theoretical model for MRF, Don Golini took the empirical approach that a spot shape (removal function) from the process could be measured and needed—somehow—to be used to derive a toolpath for deterministic figure correction. However, the tool paths that were tried always made the optical figure worse instead of better. A student working at COM recommended to Don Golini that he talk to Prof. Greg Forbes of the university’s Institute of Optics. Greg’s first impression of MRF was that “there was just a rotating turntable with a lot of goop on it.”

Forbes and his student Paul Dumas began to collaborate with Don Golini in 1993, working on models for spherometer metrology and ring tool grinding. Forbes and Dumas also began to create MRF polishing algorithms. Their algorithm was first tested in the lab on 30 March 1994. By 17 June, MRF was able to improve the optical figure of a spherical part by a factor of 4.5 in a single cycle.

In June and July 1994, Greg made his most concentrated effort to devise algorithms for MRF polishing. He insisted that his student, Paul Dumas—rather than a software professional—be hired to work with him. Greg later explained that Paul was very strong at computer programming and in mastering the program development environment of the hardware. "Paul had the uncanny ability to store the toolbox of routines in his head and use it. He had the directory in his head."

Paul Dumas (Figure 18) was born in Whitinsville, Massachusetts in 1968. He received a Bausch & Lomb scholarship to the University of Rochester, where he earned a BS in optics in 1990. He immediately enrolled in the PhD program and eventually chose to work with Greg Forbes on aspheric lens design. Three years into his PhD program, he discovered himself working on MRF with Forbes.

The Forbes-Dumas code takes three inputs:[15] (i) an interferogram showing the spot (removal function) made by MRF on the glass material, (ii) an interferogram showing the initial shape of the workpiece, and (iii) the processing objective such as uniform removal of the damaged surface layer or figure correction, or both. The code derives a set of instructions for the spindle arm angular controller of the MRF machine. The code specifies angles and accelerations, the number of sweeps between positive and negative angles, and total processing time to reach a predicted final shape (Figure 19).



(a) Polishing spot (b) Initial figure (c) Predicted final figure (d) Observed final figure

Figure 19. Input(a, b) and output (c) of the Forbes-Dumas code, along with observed result of polishing operation (d).

The first step involves mechanical calibration and the registration of metrology to enable the control of six independent motors in order to position the tool at any desired location in the part's metrology map, and be able to predict the form of the removal rate in each location. The next challenge is to determine how to move the tool to correct a part's current figure error while leaving behind only negligible traces of the tool's path. The ultimate goal is to achieve this correction with the least possible polishing time (hence minimal material removal) while respecting limits on travel, speed, and acceleration of the drive systems.

Forbes developed polishing algorithms in C++ and Dumas built the full-blown Windows code to implement the algorithms on the trough machine. Much of the time, Forbes and Dumas worked together side by side staring at the same computer screen. Forbes had to decide where the tool should begin and end its motion and what to do when the tool comes to the edge of the workpiece. It was "most natural" to start with glass out of the fluid, smoothly bring the tool to the glass, take it to the center of glass, and off the other side of the glass. The "tool" is the magnetically stiffened MR fluid. Should rotation of the trough or the rotation of the workpiece be the main motion affecting material removal? It was decided to move the fluid at right angles to the workpiece velocity at the point of contact to decouple the two motions and keep the footprint as constant as possible. Dumas wrote a graphical user interface for the operator that interacted with Zygo metrology files, generated a toolpath and dwell times with the Forbes algorithm, and controlled the CNC machine to execute those instructions.

In four to six months, the Forbes-Dumas algorithms and software were driving the MRF machine to make rotationally symmetric figure corrections in lenses. Forbes was delighted with the proof-of-principle that the algorithm worked and Don Golini was inspired to think about commercialization of the technology. The algorithm predicted how long it would take and what the final shape would be. As Steve Jacobs stated, if the predicted result was not good enough, "you could dip the part deeper or shallower into the fluid and see what the result would be—all by computer prior to any experiments." Corrections necessarily had rotational symmetry because of the constant rotation around of the spindle about the A axis in Figure 15. Only later when the QED prototype machine was built in 1997 was there control of dwell time in different clocking orientations of the workpiece to make non-rotationally symmetric corrections. Algorithms and software were refined in the period 1994 to 1996 to address issues such as center and edge artifacts. Algorithm development for correction of non-rotationally symmetric errors began in 1996.

A measure of improvement for figure correction is the *convergence factor*, defined as

$$\text{Convergence factor} = \frac{\text{root-mean-square figure error before correction}}{\text{root-mean-square figure error after correction}}$$

Depending on many conditions, attainable convergence factors could be in the range 2 or 3 up to 10 for MRF correction. By June 1994, MRF achieved a convergence factor of more than 4 with root-mean-square surface roughness below 1 nm for simple lenses. Over the years, a major goal has been to achieve similar convergence factors on workpieces with larger (up to 2 m) and smaller (down to 3 mm) and more complex shapes (off-axis, freeform, prism, hexagonal aperture).

In 1994, Forbes moved back to Australia for family reasons and became a Research Professor of Physics at Macquarie University in Sydney. Three Ph.D. students, including Paul Dumas went with him. Greg and Paul continued to support MRF development from Australia. In 1996 when Don Golini was planning to start a company, he asked Dumas to come back and be his software manager. Forbes advised Paul that this was such a wonderful opportunity that Paul ought to take it even though Paul knew full well that he might never complete his PhD. "In fact, he [Paul] never looked back," said Forbes. Paul moved back to Rochester and became a founding member of the company.

FLUID AND TROUGH HARDWARE DEVELOPMENT

For deterministic finishing, the material removal function must be constant for a long enough period of time to make figure corrections (Figure 20). Steve Jacobs' group and scientists from Minsk worked for five years to stabilize and optimize the MR fluid[16] and to understand the mechanism of magnetorheological finishing. The initial recipe for fluid came from Minsk in 1993. "They had to bring over Alina Matsepuro, who was part of their team. She had a large mortar and pestle with a wooden handle and a ceramic tip and she was the only person who could make the MR fluid right…. We spent the next few years trying to figure out how [the fluid] worked." By the end of 1993, the mortar and pestle had been replaced by a reproducible procedure using a ball mill at COM.

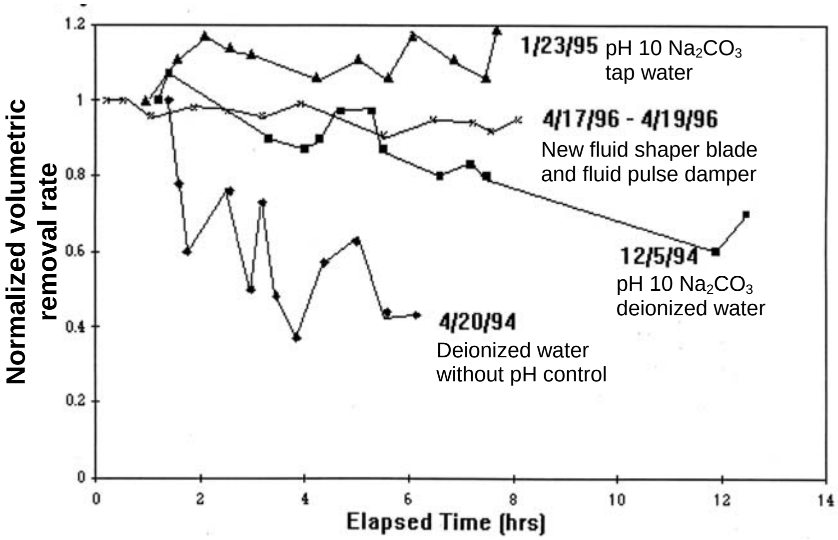


Figure 20. Improvements in stability of MR polishing spot over time achieved by chemically stabilizing the fluid and improving the fluid delivery system.

The magnetorheological fluid contains magnetic iron particles (~36 vol%), abrasive particles (~6% vol%), stabilizers (~3 vol%), and water. When the fluid stiffens in a magnetic field, abrasive particles are expelled toward the outer surface of the fluid (Figure 21). When they contact the workpiece, abrasive particles are pushed back down into the MR fluid, so the forces between the abrasive and the workpiece are not very great. Separation of the abrasive from the iron required that the fluid be homogenized elsewhere in the trough before it returned to the magnetic field.

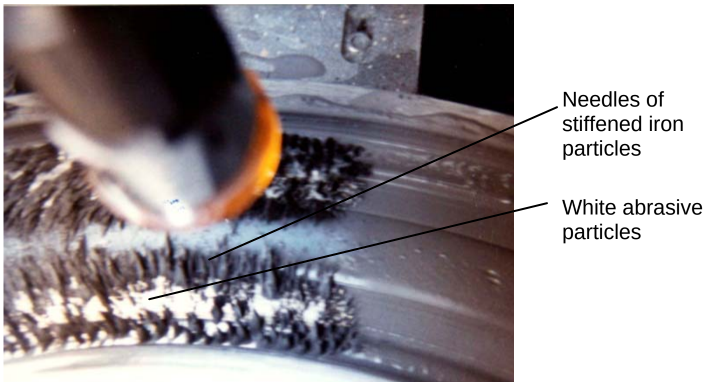


Figure 21. White abrasive particles observed at the top of the stiffened MR fluid in the trough beneath the workpiece.

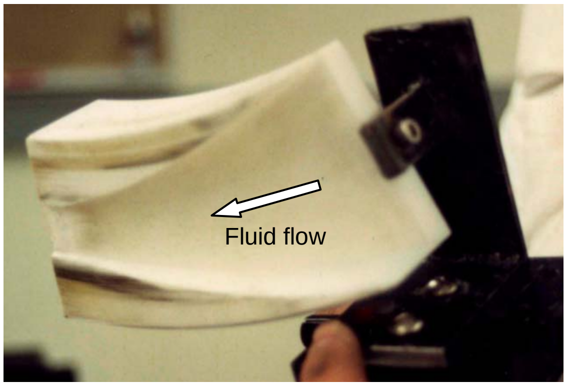


Figure 22. Bottom view of Teflon shaper placed in trough to channel fluid into a narrow stream at the workpiece.

Most of the fluid in the trough never contacted the workpiece. A Teflon shaper (Figure 22) was placed in the trough to extrude a ribbon of MR fluid that went into the magnetic field and contacted the workpiece. Channeling the fluid in this manner reduced the amount of fluid required for polishing and, more importantly, reduced the area from which water evaporation could occur.

A second critical advance in stabilizing the material removal function for long periods of time was continuous replacement of evaporated water from the fluid. An instrument to measure viscosity of the fluid was installed in the trough when it was not in the magnetic field (Figure 23). A feedback loop controlled a peristaltic pump that added water back to the fluid to keep the viscosity constant.

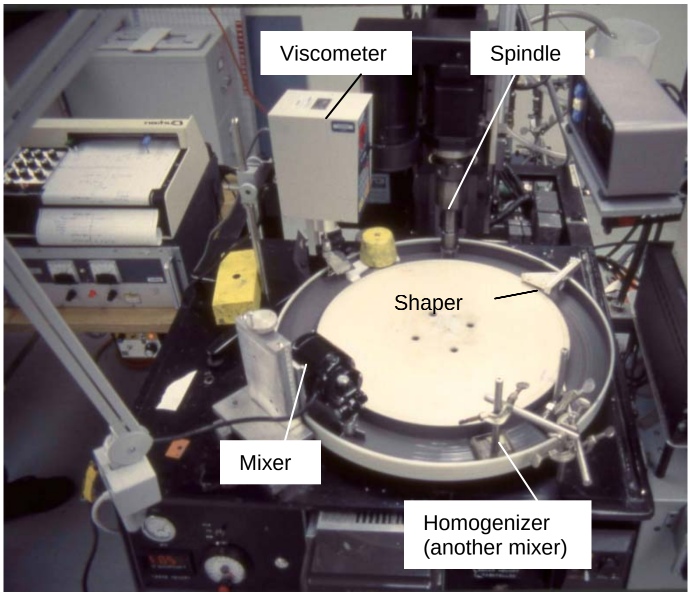


Figure 23. Configuration of trough machine incorporating advances of the first year of development at COM.

Figure 24. *Left to right:* Vladimir Kordonski, Ed Fess, and Igor Prokhorov at COM in September 1994.

A key source of degradation of the MR fluid was oxidation of the iron particles by oxygen in the aqueous suspension. Around Christmas of 1994 Vladimir Kordonski (William's son, Figure 24) and Steve Jacobs discovered that the addition of sodium carbonate as a buffer to the MR fluid stabilized the pH near 10 and gave a stable polishing spot for 8 hours. Raising the pH to inhibit corrosion of iron was one of the most important breakthroughs enabling advances in the deterministic polishing process.

The period 1994 to 1996 saw improvements in the delivery of MR fluid. Instead of filling the whole trough, fluid was delivered in a compact ribbon immediately upstream of the workpiece and sucked off the trough immediately downstream (Figure 25). This process minimized evaporation of water and further stabilized the material removal function. Fluid was stored in a reservoir between the delivery tube and collection tube. The fluid was homogenized and its moisture restored in the reservoir so that the fluid delivered to the workpiece had constant performance for many hours (Figure 20). A blade was added between the delivery nozzle and the workpiece to shape the ribbon of fluid for best performance (Figure 25).

In February 1995, the third polymeric trough used between 1993 and 1995 was replaced with an aluminum trough. Grooves had been worn into each polymeric trough. Also, MR fluid attracted by the magnet would warp the polymeric trough. The stiffer aluminum trough had little deflection and therefore kept the gap between the workpiece and the MR fluid more constant.

Concurrent with development at COM, the group in Minsk was working to create a fluid delivery system (Figures 26 and 27). A truly international collaboration orchestrated by Byelocorp Scientific was in progress.

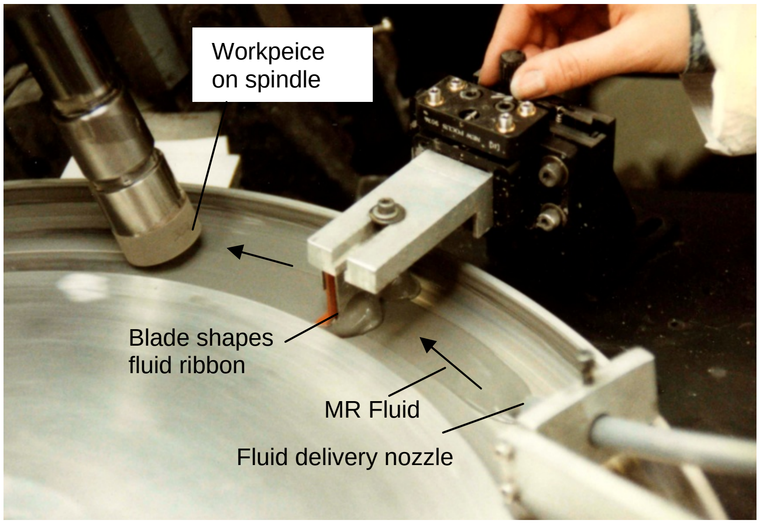


Figure 25. MR fluid delivery at COM in April 1996. A ribbon of fluid is delivered from the tube on the lower right and shaped by the blade at the center. After fluid passes the workpiece and is out of view in this photo, it is sucked back into a reservoir where it is continually reconditioned.

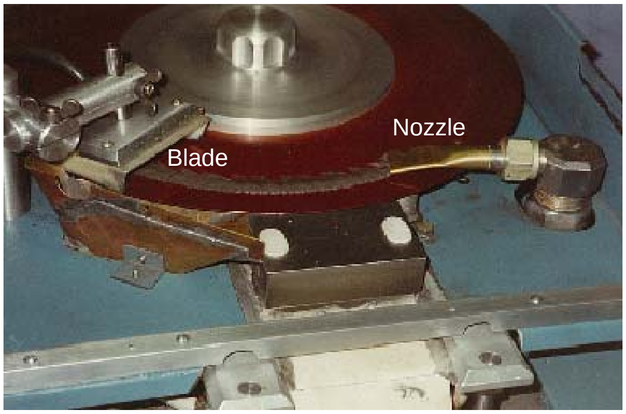


Figure 26. Fluid delivery system with pump, nozzle, blade at Minsk in 1994.

Figure 27. *Left to right:* William Kordonski, Don Golini, Igor Prokhorov, and Lowell Mintz in Minsk in 1994.

ASPHERES, AT LAST!

In 1995, the trough machine was used to demonstrate polishing and figure correction of aspheric lenses in a collaboration with Texas Instruments.[15] Plano-convex BK7 glass test parts with a diameter of 47 mm had 140 µm of aspheric departure. Parts ground with an OPTICAM machine at Texas Instruments had residual peak-to-valley form errors of 4 to 20 µm and surface roughness as great as 10 000 Å. The upper trace in Figure 28 shows the deviation of the ground part from the desired aspheric form measured with a stylus profilometer. The middle trace shows the surface error after 100 min for uniform removal of 12 µm of subsurface-damaged material by MRF. Roughness has been reduced from 9 400 Å to 10 Å and the peak-to-valley error was reduced from 6.4 to 4.4 µm. The bottom trace shows figure correction to 0.86 µm error with one 40 min MRF cycle and 4 µm of material removal. The 3-axis prototype machine described next was even better suited to making aspheres.

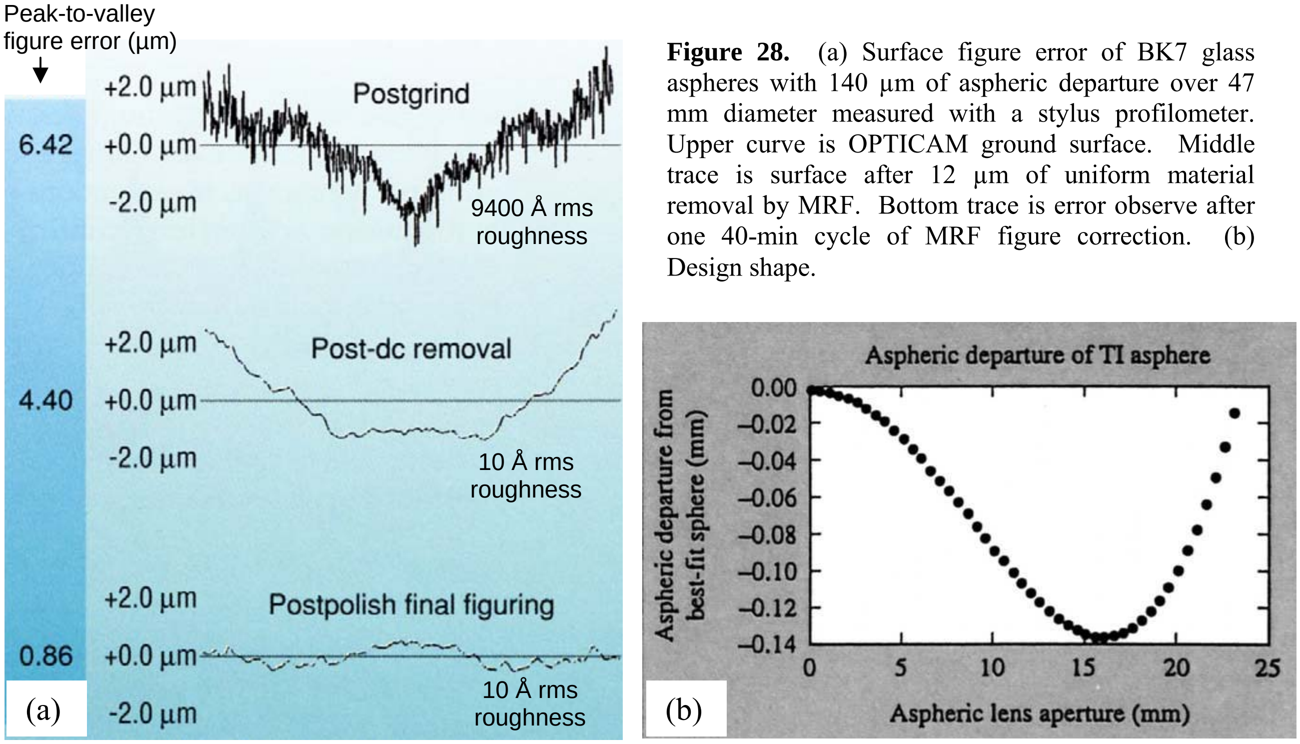
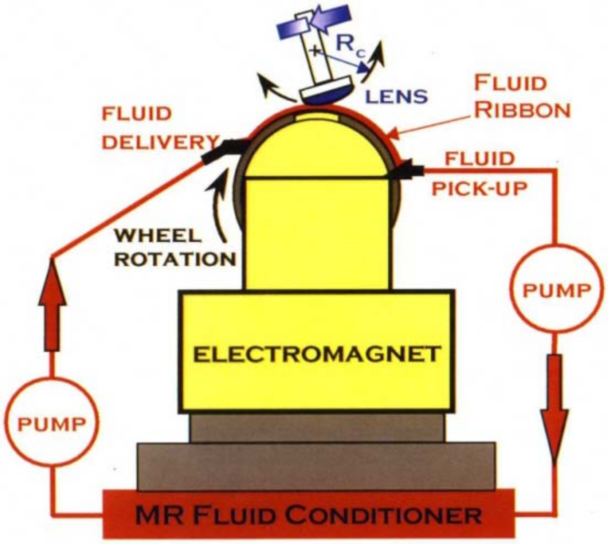


Figure 28. (a) Surface figure error of BK7 glass aspheres with 140 µm of aspheric departure over 47 mm diameter measured with a stylus profilometer. Upper curve is OPTICAM ground surface. Middle trace is surface after 12 µm of uniform material removal by MRF. Bottom trace is error observe after one 40-min cycle of MRF figure correction. (b) Design shape.

PROTOTYPE MRF MACHINE: THE VERTICAL WHEEL

In 1995 William Kordonski had the inspired idea to replace the trough that had been in use since the inception of MRF with a more versatile vertical wheel. Fluid would be injected onto the wheel just ahead of the workpiece and retrieved just beyond the workpeice (Figure 29). A patent was filed in October 1995.[17]



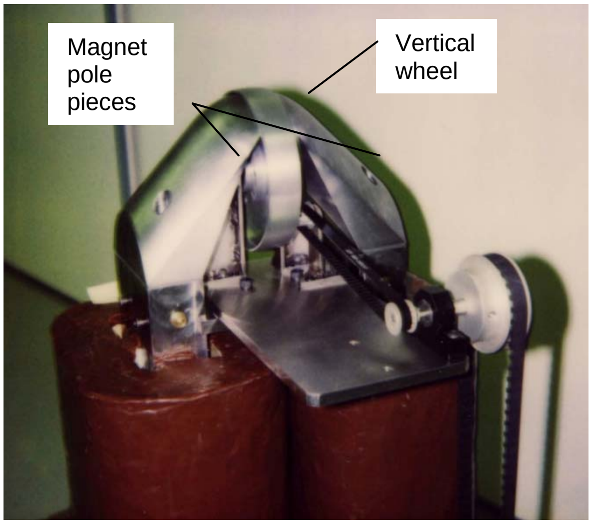


Figure 29. William Kordonski's idea for a magnetorheological fluid polisher with vertical wheel replacing horizontal trough. Photo shows prototype unit constructed in April 1995.

The trough machine was restricted to polishing convex surfaces. A vertical wheel could work on a plano surface or a shallow concave surface (Figure 30).[18]

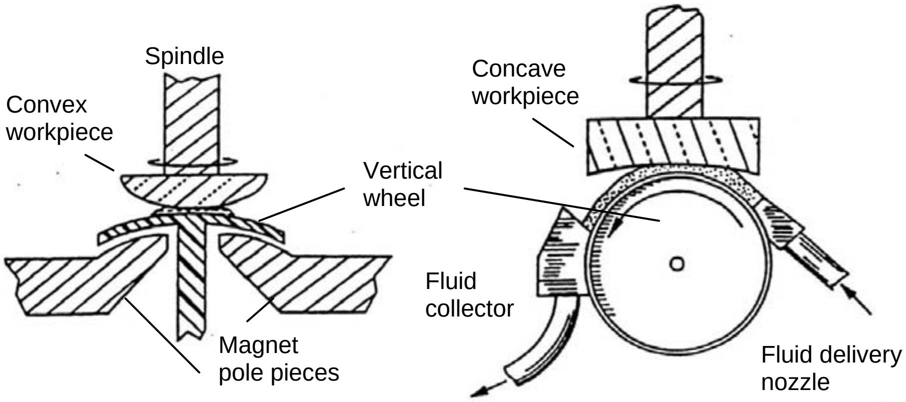


Figure 30. *Left:* Cross-section view of convex wheel rim and electromagnetic pole pieces. *Right:* Side view of wheel and fluid delivery and recovery system.[18]

The prototype MRF polishing machine in Figure 31 with a vertical wheel was constructed by CNC Systems (later OptiPro) and delivered to COM in 1996. This machine has 3 CNC degrees of freedom with translation along X and Z in Figure 32 and rotation about B. The combination of X, Z and B allows software to sweep a rotating lens through the fluid about a virtual pivot point, enabling aspheres to be made in a deterministic manner. The wheel and magnet assembly could be rotated manually by 90° about the C axis to adjust the relative motions of the fluid and the spindle. Constant rotation of the spindle still restricted the machine to rotationally symmetric corrections. Reconditioning of the circulating fluid in a reservoir maintains the fluid viscosity and temperature to provide a constant material removal rate for 8 h. Fluid stability is a key enabler that made magnetorheological fluid finishing practical.

Figure 31. *Left:* Prototype MRF machine with vertical wheel operating at COM in March 1996 with Ed Fess at the controls. *Right:* Workpiece on spindle positioned over vertical wheel.

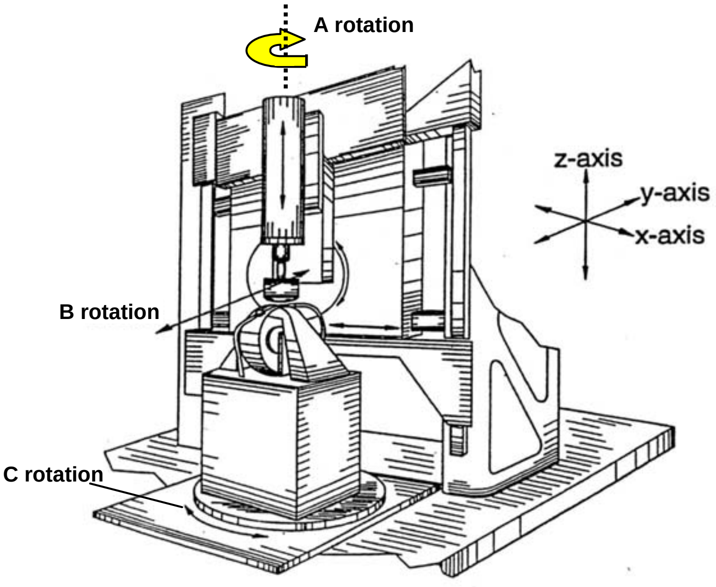


Figure 32. Translation and rotation axes for CNC machine tool. The 1996 MRF prototype machine controlled X and Z translation, as well as rotation about B. The spindle (A-axis) rotated at a constant rate. The 4-axis commercial Q22 MRF machine built in 1998 commanded translation along X and Z and rotation about B and A (spindle). Control of the A-axis (clocking of the workpiece) allows for the correction of figure errors that do not have rotational symmetry. The 5-axis Q22-Y developed in 2000 added the Y-axis for rastering. Rastering in the X-Y plane allows plano parts to be machined and permits automatic centering of rotationally symmetric parts.

THE BIRTH OF QED

Lowell Mintz's plan in forming his company BSI was to commercialize technology from Minsk. When work started at COM, Lowell began to attend optics trade shows. He found that "there was absolutely no belief in this [MRF] whatsoever." In 1994, COM had an open house for visitors from industry. "Everyone would look at the machine. They would put their finger in the fluid and would be shaking their heads." By late 1995, Harvey Pollicove ("whose only hallmark of success was industry implementation") was asking Lowell what he planned to do with MRF. Normally, the University would give a royalty-free license to its industrial sponsor. However, Mintz owned the MRF patent and it was up to him to decide what to do with it. Harvey had told Lowell that Don Golini "had an entrepreneurial streak."

By 1996, part of Don Golini's job at COM was to visit companies and publicize MRF capabilities, but there was no way for a company to buy an MRF machine. Don decided that it was time to commercialize MRF and he would be the one to

Don Golini Steve Hogan Paul Dumas William Kordonski Hugh Edwards

Figure 33. Opening day employees of QED Technologies in January 1997 in front of the 3000-square-foot facility at 1080 University Avenue in Rochester. “We shampooed the floors together on the first day,” according to Hogan.

do it. He spent six months writing a business plan that was finished in July 1996. For this purpose, he conducted market surveys, interviewed prospective customers, and made financial projections.

Don knew he would have to license MRF technology from BSI and would have to raise capital. Lowell Mintz studied Don’s business plan and was sufficiently impressed to become sole investor and equal partner, with shares set aside for people to be hired. Mintz provided loans and licensed MRF technology to the company. The informally designated “magnetorheological finishing company,” was incorporated in December 1996. The Advisory Committee consisted of Paul Forman of Zygo Corp., Sue Hartman, a consultant and former Kodak executive, Peter Ciaccia, a financial expert, and Paul Jacobs, a lawyer. Later, David Lovenheim, a local lawyer and entrepreneur, and Nancy Catarisano, Peter Ciaccia's partner, joined the group of advisors. The Golini’s two-day-old third child, Catie, attended the first board meeting in January 1997.

Don Golini intended to return home to Boston and expected that the company would be located near Boston. However, after looking at the housing and job markets, he chose to stay in Rochester where costs were lower and people could be easily recruited from the University of Rochester. Over time, the company made good use of student interns and was then able to offer jobs to some of them. In Rochester, the company would be close to its expected main customer base.

The company needed a name. In early 1997, Don Golini was brainstorming over lunch with Professor John Lambropoulos of the University of Rochester. Seeking a name from Greek, they came up empty. Then Lambropoulos said, “why don’t you go with Latin?” and he proposed “QED” (that which was to be demonstrated”). And so it was.

The company began with five employees (Figure 33). William Kordonski managed research and development for MR fluids, magnets, and hardware. Paul Dumas was recruited from Australia for software development, applications/process engineering, and information technology. Dumas noted that the “little side project” he was pulled into as a graduate student three years earlier “kind of blossomed.” Steve Hogan, born in Glenns Falls, New York in 1963, was Don Golini’s classmate at Rochester and roommate while Don worked on his master’s degree. Hogan worked at the General Motors Delco plant in Rochester for 11 years in maintenance and manufacturing. He was an electrical engineer whose experience qualified him to be QED’s mechanical systems designer and operations manager. Hogan “made everything happen at the company,” according to Dumas. When QED began to sell machine tools, Hogan did the physical installation and troubleshooting and Dumas handled process support and training for the customer. Dumas would devise a method for a customer to polish a particular part. The fifth original employee of QED was Hugh Edwards, a technician who came from COM. Hugh was most familiar with operating the machines and keeping them running. He executed experiments, helped develop hardware, and conducted demonstrations for prospective customers.

Greg Forbes continued part time from Australia to support product development. In 2000, Forbes resigned from Macquarie University to become a full-time Australia-based employee of QED, which he remains in 2011. Forbes played a principal role in the development of subaperture stitching in the 2000s. After it was formed, QED continued to fund Steve Jacobs’ work at COM in product development for three or four years. Jacobs remained as a consultant for QED until 2009. Jacobs’ student, Aric Shorey, wrote the first PhD thesis on magnetorheological finishing in 2000. Two more PhD theses were completed in 2007 by Jessica DeGroote Nelson and in 2010 by Chunlin Miao.

QED PRODUCTS

QED opened its doors in January 1997. By the end of the year, the prototype of the first commercial 4-axis MRF machine called Q22 had been assembled (Figures 34 and 35). Three production machines were ready to ship in 1998. The first customer, Tropel, was followed by Kodak and SVG Lithography. Serial number 1 was installed at Tropel in Rochester in December 1998. Six units were shipped in 1999 and 20 in 2000. In the name “Q22,” Q was from QED and 22 was Don Golini’s lucky number.

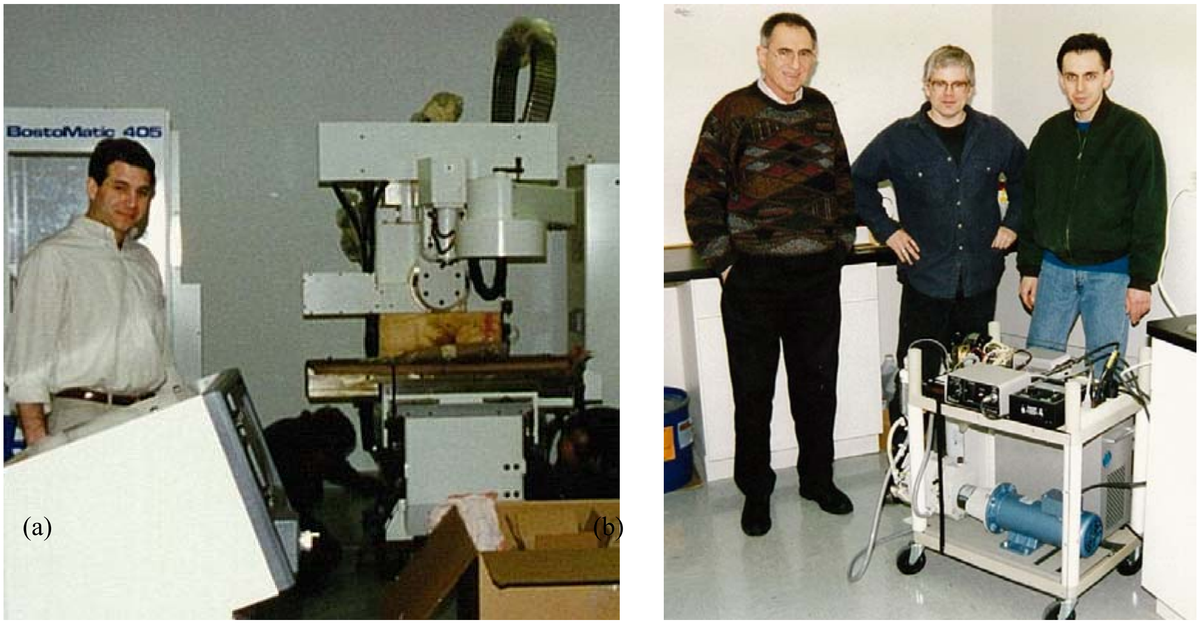


Figure 34. (a) Don Golini with theBD-405 platform used to build the prototype Q22 MRF machine in 1997. (b) *Left to right:* William Kordonski, Hugh Edwards, and Vladimir Kordonski with the fluid delivery system.

The Q22 was a 4-axis machine similar to the 3-axis prototype machine in Figure 31 built for COM by CNC Systems in 1996. The Q22 controls translation in the X and Z directions and rotation about the B and A (spindle) axes (Figure 32).

A-axis control enables the correction of figure errors that are not rotationally symmetric. The workpiece is commanded to spend more time being polished in some rotational orientations and less time in others.

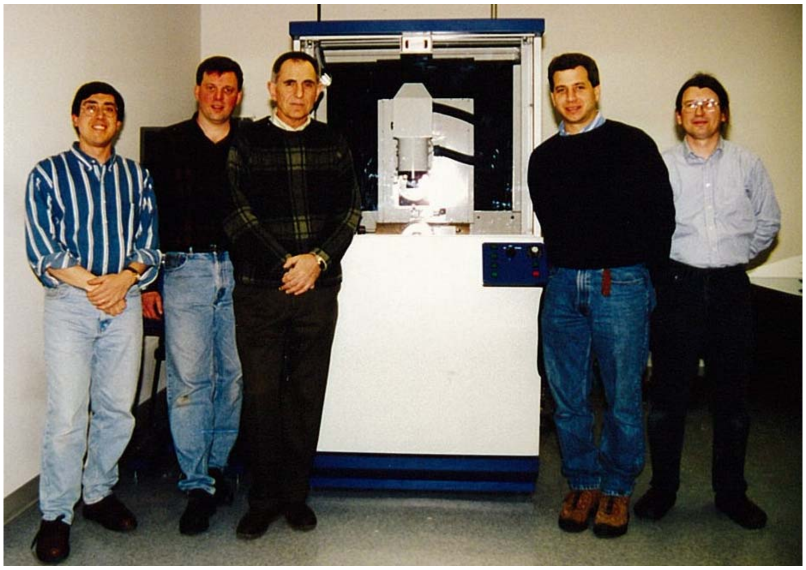


Figure 35. Finished Q22 prototype in 1998. *Left to right:* Paul Dumas, Steve Hogan, William Kordonski, Don Golini, and Arpad Sekeres.

QED found the BD-405 Boston Digital 5-axis milling platform to be suitable for a prototype Q22. The BD-405 was too large to fit into most optics shops, so the smaller 4-axis BD-12 platform was developed for the first 25 Q22 machines that were shipped. Steve Hogan produced the mechanical design. When Hugh Edwards left QED in the first year, tool maker Arpad Sekeres was hired to fabricate hardware using a rebuilt mill and lathe that QED acquired. Paul Dumas developed the software. The fluid delivery system was refined to further increase the stability of the polishing spot, which was absolutely essential for deterministic finishing. Hogan would transport the MRF unit built at QED in the back of his truck to Boston Digital, where it was integrated with the milling platform. From there, Hogan would transport the finished Q22 machine to a customer.

The ability to make figure corrections on aspheres was the lynchpin to customer interest and commercial sales. Deterministic correction of aspheres was an enabling technology for the optics industry. Nonetheless, QED was pleasantly surprised to discover that most customers were making spherical optics with MRF. Because the machine was so expensive in comparison with traditional equipment, it was employed to manufacture the highest quality optics. Users found that they could make better spherical optics at lower cost with MRF.

The next step for QED was to add Y-axis control (Figure 32) in the Q22-Y introduced in 2000. The Y-axis enables raster polishing of planar optics and automatic centering of rotationally symmetric parts. Up to this point, centering a part for rotational polishing was a labor intensive operation for a skilled worker. The Q22-Y and subsequent QED machines were built on Schneider Optical Machinery platforms using Siemens motion control, rather than on Boston Digital platforms. Schneider understood the optics industry and requirements for precision and vibration damping. High resolution digital spindle rotational control on the Schneider platform replaced analog rotational control on the earlier Q22, decreasing servo lag.

“You can’t make what you can’t measure.” Early in its existence, QED realized that it needed more metrology than was commercially available to support MRF. Improved metrology was required for optics with larger diameters, higher numerical aperture, and more complex shapes such as aspheres. Existing interferometers could only measure deviations of a few microns from a spherical surface. Development of the QED Subaperture Stitching Interferometer (SSI) began around 2002 to produce the first commercial offering in 2004. The first generation SSI could measure deviations up to a few tens of microns from a spherical surface and had an immediate market for measuring larger diameter and higher numerical aperture optics. The Aspheric Stitching Interferometer (ASI) introduced in 2009 provides greater ability to measure aspheric optics with up to a few hundred microns of departure from a spherical surface.

Around 2002, QED developed a magnetorheological fluid jet (MR Jet), which remains experimental in 2011. The jet shoots a stream of MR fluid through a nozzle in a magnetic field. The fluid stream maintains its cylindrical shape for a distance on the order of 30 cm and can be used to remove material from inside deep concave shapes that cannot be reached by an MRF wheel.

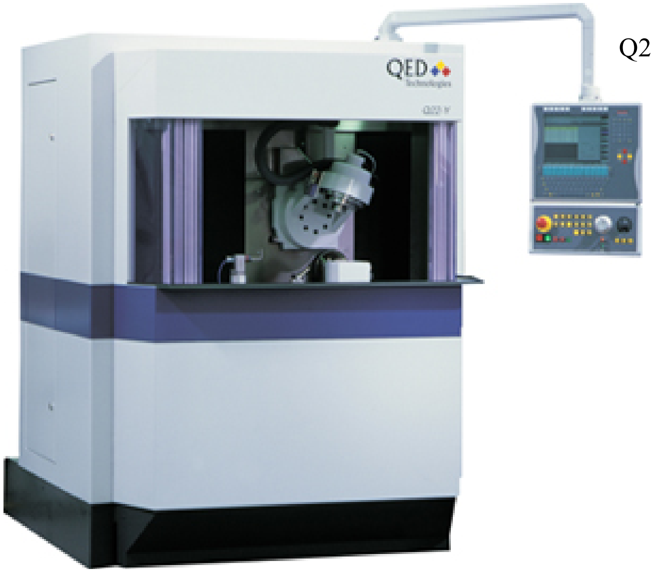
QED was rapidly recognized for its seminal contribution to the optics industry. The Q22-Y MRF machine and the Aspheric Stitching Interferometer were each honored by R&D Magazine with R&D 100 awards for the most technologically significant products introduced into the marketplace. The 2000 Defense Manufacturing Technology Achievement Award for deterministic MRF finishing was shared by Stanley Kopacz, Walter Roy, and Robert Volz of the U.S. Army, Steve Jacobs and Harvey Polllicove of the Center for Optics Manufacturing, and Don Golini and William Kordonski of QED.

In 2006, Cabot Microelectronics Corp. acquired QED Technologies and the patents owned by Byelocorp Scientific for approximately $20 million. QED had grown from 5 people in 1997 to about 40 people when it was acquired. Its polishing machines and interferometers could be found throughout the optics industry.

EPILOG

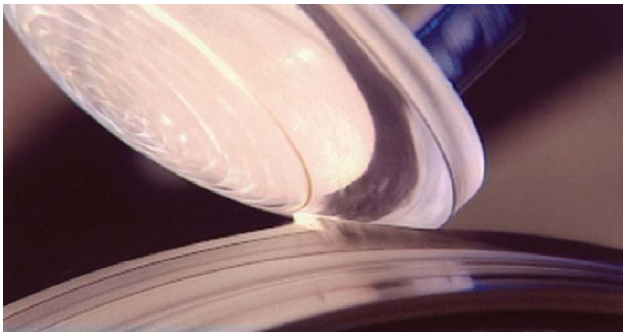
Reflecting events, Lowell Mintz described the role of serendipity in the story of MRF and QED. “The wonderful part of the story is that … if my best friend in college had not been a physicist and had not worked for an optical company, I would not have known who to call. If Steve Jacobs had not been walking by Harvey’s office … we would still be scratching our heads. If Steve hadn’t had a vacation coming up, he couldn’t have gone to Minsk.”

William Kordonski summed up his account with these observations. He could not believe that five people in one year could design and build the Q22. Nowhere else in the world could this work be accomplished so effectively. The most interesting thing William learned was *trust*. Lowell Mintz needed to know that there was worthwhile technology and William wanted to make sure the “know how” would be in the right hands. It took time and effort before the two men developed mutual trust. As a result, a great deal of “know how” was developed along the road and protected by 22 U. S patents and numerous foreign patents. Entrepreneurial spirit and investment in the U.S. provided a unique opportunity to turn a scientific idea into reality such that the world’s optical industry now enjoys a unique, high-precision finishing technology.



Q22-Y R&D 100 Award winner 2001

Making a lens. Notice the fluid between the glass and the MRF wheel.



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