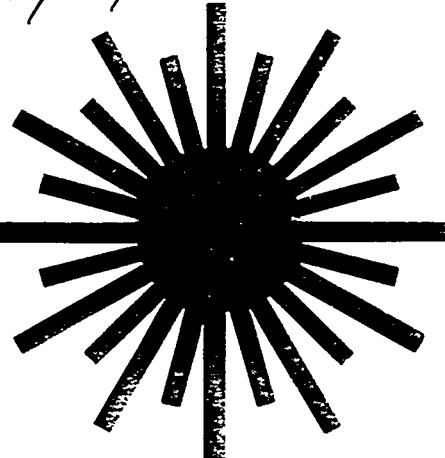


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**1998 SUMMER RESEARCH PROGRAM FOR HIGH SCHOOL JUNIORS**

AT THE

UNIVERSITY OF ROCHESTER'S

LABORATORY FOR LASER ENERGETICS

STUDENT RESEARCH REPORTS

PROJECT COORDINATOR

Dr. R. Stephen Craxton

March 1999

Laboratory Report 300

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**Laboratory for Laser Energetics**

University of Rochester

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**STUDENT RESEARCH REPORTS**

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**Dr. R. Stephen Craxton**  
LABORATORY FOR LASER ENERGETICS  
University of Rochester  
250 East River Road  
Rochester, NY 14623-1299

During the summer of 1998, 11 students from Rochester-area high schools participated in the Laboratory for Laser Energetics' Summer High School Research Program. The goal of this program is to excite a group of high school students about careers in the areas of science and technology by exposing them to research in a state-of-the-art environment. Too often, students are exposed to "research" only through classroom laboratories that have prescribed procedures and predictable results. In LLE's summer program, the students experience all of the trials, tribulations, and rewards of scientific research. By participating in research in a real environment, the students often

become more excited about careers in science and technology. In addition, LLE gains from the contributions of the many highly talented students who are attracted to the program.

The students spent most of their time working on their individual research projects with members of LLE's technical staff. The projects were related to current research activities at LLE and covered a broad range of areas of interest including optics, spectroscopy, chemistry, diagnostic development, and materials science. The students, their high schools, their LLE supervisors and their project titles are listed in the table. Their written reports are collected in this volume.

The students attended weekly seminars on technical topics associated with LLE's research. Topics this year included lasers, fusion, holography, nonlinear optics, global warming, and scientific ethics. The students also received safety training, learned how to give scientific presentations, and were introduced to LLE's resources, especially the computational facilities.

The program culminated with the High School Student Summer Research Symposium on 26 August at which the students presented the results of their research to an audience that included parents, teachers, and members of LLE. Each student spoke for approximately ten minutes and answered questions. At the symposium an Inspirational Science Teacher award was presented to Mr. David Crane, a chemistry teacher at Greece Arcadia High School. This annual award honors a teacher, nominated by alumni of the LLE program, who has inspired outstanding students in the areas of science, mathematics, and technology.

High School Students and Their Projects (1998)			
Student	High School	Supervisor	Project
Steven Corsello	Pittsford Mendon	K. Marshall	Computer-Aided Design and Modeling of Nickel Dithiolene Near-Infrared Dyes
Peter Grossman	Wilson Magnet	R. S. Craxton	Group Velocity Effects in Broadband Frequency Conversion on OMEGA
Joshua Hubregsen	Pittsford Sutherland	S. Jacobs	A Study of Material Removal During Magnetorheological Finishing (MRF)
Nieraj Jain	Pittsford Sutherland	M. Guardelben	Analyzing Algorithms for Nonlinear and Spatially Nonuniform Phase Shifts in the Liquid Crystal Point Diffraction Interferometer
Leslie Lai	Pittsford Mendon	M. Wittman	The Use of Design-of-Experiments Methodology to Optimize Polymer Capsule Fabrication
Irene Lippa	Byron-Bergen	K. Marshall	Synthesis and Analysis of Nickel Dithiolene Dyes in a Nematic Liquid Crystal Host
Phillip Ostromogolsky	Brighton	F. Marshall	Investigation of the X-Ray Diffraction Properties of a Synthetic Multilayer
Michael Schubmehl	The Harley School	R. Epstein	An Analysis of the Uncertainty in Temperature and Density Estimates from Fitting Model Spectra to Data
Joshua Silbermann	Penfield	P. Jannimagi	Automated CCD Camera Characterization
Abigail Stern	The Harley School	J. Knauer	Design and Testing of a Compact X-Ray Diode
Amy Turner	Churchville-Chili	R. S. Craxton	Ray Tracing Through the Liquid Crystal Point Diffraction Interferometer

A total of 91 high school students have participated in the program since it began in 1989. The students this year were selected from approximately 60 applicants. Each applicant submitted an essay describing their interests in science, a copy of their transcript, and a letter of recommendation from a science or math teacher.

LLE plans to continue this program in future years. The program is strictly for students from Rochester-area high schools who have just completed their junior year. Applications are generally mailed out in February with an application deadline near the end of March. For more information about the program or an application form, please contact Dr. R. Stephen Craxton at LLE.

This program was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.

A STUDY OF MATERIAL REMOVAL DURING  
MAGNETORHEOLOGICAL FINISHING

by

JOSHUA HUBREGSEN  
Pittsford Sutherland High School  
Pittsford, NY

# A Study of Material Removal During Magnetorheological Finishing (MRF)

Joshua J. Hubregsen

Advisor: Dr. Stephen D. Jacobs

LABORATORY FOR LASER ENERGETICS  
University of Rochester

Summer High School Research Program  
1998

## Abstract

In the process of optical polishing, a new method has been developed called Magnetorheological Finishing, or MRF. This process utilizes both mechanical and chemical effects to remove material during polishing. To more fully understand the fundamental mechanisms of MR polishing we have successfully separated mechanical scratching from chemical softening in glass polishing with MRF by removing the water from the MR fluid. The addition of water initiates the chemical effects by hydrating the glass surface and changing the amplitude of the scratches. In addition, this study has found that the mechanical removal by scratching is related to the hardness of the magnetic carbonyl iron particles, and the hardness and type of the glass being polished.

## Introduction

In traditional optical finishing, a skilled optician is required to polish the glass lens. The process is an iterative trial and error, non-deterministic process. First, the optician polishes the lens and then he or she must use metrology tools to analyze surface roughness. If the part does not meet specifications, more polishing and analysis is required until it is satisfactory. This time consuming process requires hours or even days of polishing. When polishing a lens, each radius of curvature requires a special polishing pad. This pad must be reconditioned or even changed to maintain the specific shape of the lens. A problem with conventional optical polishing is the manufacture of aspheric lenses. Figure 1 shows a cross section of a spherical lens and a symmetric asphere. This is just one example of a simple asphere, but they can take on a variety of different shapes. This often complex shape compounds the problems associated with nondeterministic finishing.

The process of MRF has evolved over the past few years. It was originally developed in Minsk in 1988, and the technology was brought to the United States for further development in 1993. In 1997, modifications were made which changed the design of the machine from a horizontal to a vertical wheel geometry, to increase the

machine's versatility in the polishing of aspheres. Since then, MRF has been made commercially available<sup>1</sup>.

The process of MRF is a deterministic, computer controlled polishing method which uses varying dwell time of the part in the abrasive that controls polishing over the surface of the lens. Figure 2 shows a schematic of a MR polishing machine. The wheel or trough's rotation carries MR fluid into the polishing zone, where it is acted upon by a magnetic field. An interesting property of the MR fluid is that it stiffens when placed in a magnetic field, creating a compliant MR fluid lap. This takes the role of the polishing pad in conventional optical polishing, but does not need to be reconditioned or have a specially designed radius of curvature. The spindle-mounted part rotates in the MR fluid, and the angle of the spindle also changes. Careful manipulation of these motions through computer interface allows the polishing of surfaces to the correct geometry. This versatile process gives MRF an advantage over conventional polishing in the manufacture of aspheres.

The standard MR fluid is composed of 36 percent carbonyl iron, 6 percent cerium oxide, 55 percent water, and 3 percent stabilizers. Initially, the carbonyl iron particles are spherical, with a diameter of about 4.5  $\mu\text{m}$  while the cerium oxide particles are approximately 3.5  $\mu\text{m}$  in diameter. During use, the CI tends to break the cerium oxide into smaller particles that tend to coat the carbonyl iron. This coating of the CI is seen in figure 3, which shows a SEM of CI and  $\text{CeO}_2$  after a week of use. It is believed that this improves polishing because cerium oxide is a good polishing agent that removes silica.

The MRF process has been shown to be able to polish surfaces to about 10  $\text{\AA}$  rms roughness in only a few minutes. However, this 10  $\text{\AA}$  rms appears to be a lower limit of the smoothness of MR polished parts. One question that needs to be answered is why this limitation exists in MRF. Polishing consists of hydrating (softening) the glass surface and mechanical scratching away material. Any attempt to understand smoothing with MRF must separate the chemistry from mechanics.

### Experiment

To study the polishing process in MRF, an experiment was set up to create a MR fluid where mechanics could be studied separately from the chemistry. The experiment was to make use of various types of carbonyl iron with different hardness to study the mechanics of removal for optical glasses.

In order to study mechanical removal, experiments were conducted in a slurry that contained 33 volume percent CI suspended in a non-aqueous fluid. A hard, medium-hard, and a soft carbonyl iron were used in the MR fluid to polish fused silica (FS), borosilicate (BK7), and lead silicate (SF6) optical glasses. Fused silica is used in UV applications such as the OMEGA laser, BK7 is the standard glass used in the optics industry, and SF6 has a high index of refraction, which is ideal for optical glasses. Later, two volume percent DI water was added to the MR fluid containing the hard CI in order to initiate chemical effects.

Table 1 shows the measured hardness in air of each of the materials used in the experiments. All of the hardness values were obtained using the Nano Indenter® II<sup>s</sup><sup>2</sup> at a load of 5 mN. This is a new technique to find individual particle hardness, which is used here in the Center for Optics Manufacturing.

Material	Hardness (MPa)
H-CI	11690
MH-CI	9685
S-CI	2200
FS	9790
BK7	7700
SF6	5110

Table 1

For all experiments performed, the trough rotation of the MRF machine was set at 10 rpm. An 8-amp DC current was sent to the electromagnet, which is the equivalent of 3 kGauss or 240 kA/m field in the polishing zone. The MR fluid ribbon height was 2 mm and the ribbon width was 1.5 cm. The optical glass part was lowered into the MR fluid 0.5 mm for 30 minutes without rotation of the spindle so that the shallow surface scratching occurred in one direction only. Figure 4 is a picture of what the setup looked like. Figure 4 also contains a view of the optical glass mounted in the part-holder. The disk-shaped optical glass parts used were 1.2 cm in diameter and 0.5 cm in height. They were initially pitch polished to about 8 Å rms surface roughness and were flat to .06 µm in peak to valley.

In order to analyze the surface of the optical glass part, two metrology tools were used. One was a White Light Interference Microscope<sup>3</sup> (WLIM), and the other was an Atomic Force Microscope<sup>4</sup> (AFM). The WLIM was used to measure rms surface roughness of the part, and the AFM was used to resolve shallow surface scratching. The WLIM could quickly obtain data so that three measurements could be made and then averaged for surface roughness values of a part both before and after MRF. The WLIM had a much greater measurement area than the AFM. The measurement area of the WLIM was 250 by 350 µm as opposed to the 25 by 25 µm area measured on the AFM. The WLIM has enough resolution to see that there is a difference in polishing with different fluids through an increase or decrease in roughness, but it is not always possible to see the characteristics of removal with the WLIM. Figure 5 shows a scan of the same surface with the two different instruments. While both show an increase in rms roughness, one cannot see the grooves caused by MRF in the WLIM scan, while the grooves are clearly visible in the AFM scan. The higher resolution of the AFM is useful because it can be used to investigate the mechanics of removal due to MRF. The WLIM would show the same grooves if they were on a larger scale.

## Results

The experiments showed that soft carbonyl iron is much less abrasive than hard carbonyl iron. When the hard CI was used on the soft SF6 glass, the rms roughness increased from the original rms roughness of 8 Å to about 350 Å. The hard CI increased the rms roughness to 22 Å on the medium hard BK7 glass, and on the hard FS glass, rms roughness remained at about 8 Å, which was indicative of little change. This demonstrated that when hard CI was used, roughness increased as hardness of the glass decreased. When the soft CI was used, little change occurred in roughness on all three

types of glass. We were still able to see scratches caused by the soft CI so a less aggressive removal does take place. These results proved that soft CI is much less abrasive on optical glasses. This is summarized in figure 6, which shows the rms roughness after polishing versus glass hardness for the hard and soft carbonyl iron powders. In general, the soft CI roughened the surface much less than the hard CI. Also, it is clear that the softer the glass is, the greater the roughness caused by the grooving.

Interesting results occurred when water was added into the MR fluid with the hard carbonyl iron to initiate chemical effects. On the soft SF6 glass, there was little measurable change with the addition of water. This is because the hard carbonyl iron alone had roughened the surface of the glass so much that when water was added, the reduction of surface hardness caused by hydration did not result in a significantly larger roughness. It appears that the SF6 hardness is already so much softer than the hard CI that further reduction of hardness caused by water does not significantly affect the post polishing roughness. On the fused silica glass, the addition of water to the MR fluid had an interesting effect since fused silica is close to the same hardness as the hard carbonyl iron. The AFM image of this experiment showed that the surface of the glass was pitted and that little removal had occurred. However, when water was added, the surface of the glass became hydrated and more removal and scratching occurred. The longer, deeper scratches are assumed to be a result of the lower hardness caused by the hydrated layer on the surfaces. The addition of water did not seem to have an affect on BK7, although figure 7 does suggest a different removal mechanism with the addition of water.

## Conclusion

By removing water and cerium oxide from the standard MR fluid, we succeeded in separating mechanical scratching from chemical dissolution of the surface of optical glasses in the process of MRF. As a result of this, experiments showed that mechanical removal is related to the hardness of the magnetic carbonyl iron particles, as well as the glass hardness. By adding a small amount of water into the MR fluid, the chemical dissolution of the surface was initiated, which softened the surface of the glass and changed the amplitude and type of scratching. These results will be used in the future in order to break through the 10 Å rms micro-roughness barrier that is seen in MRF using different glasses.

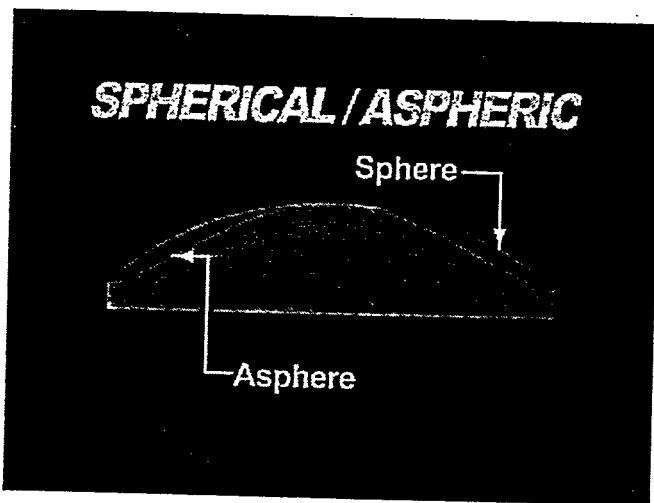


Figure 1

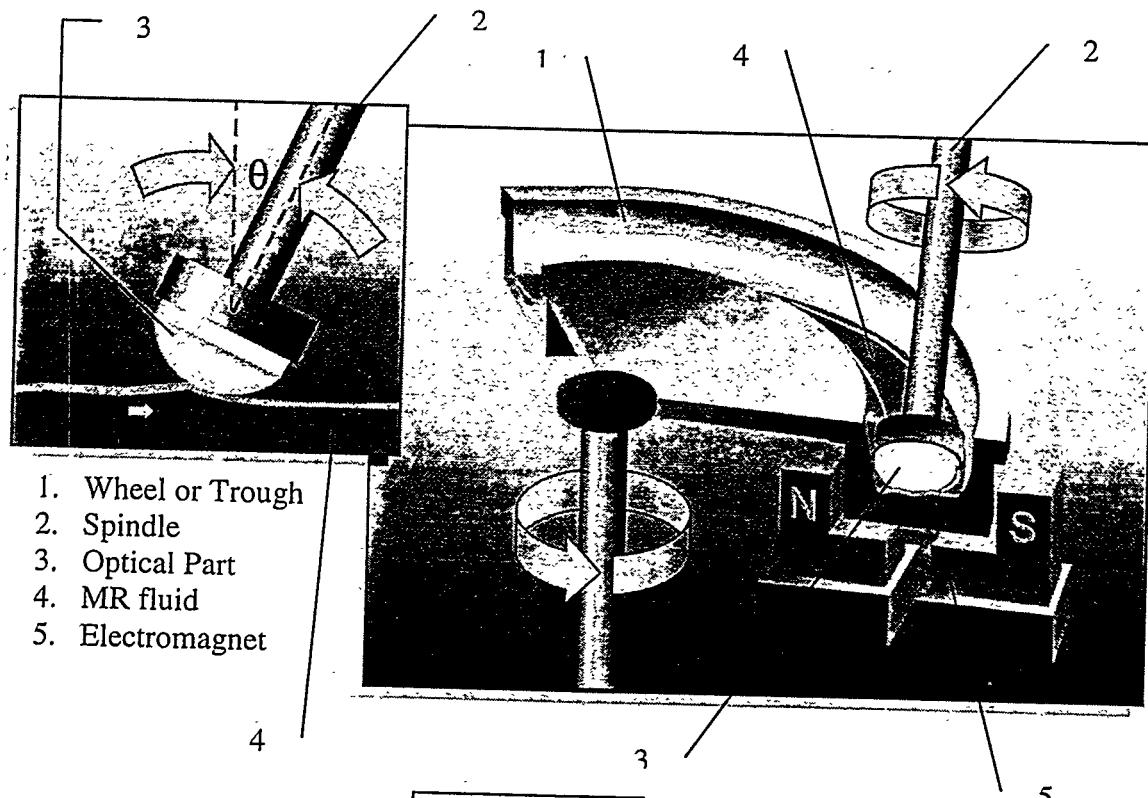


Figure 2

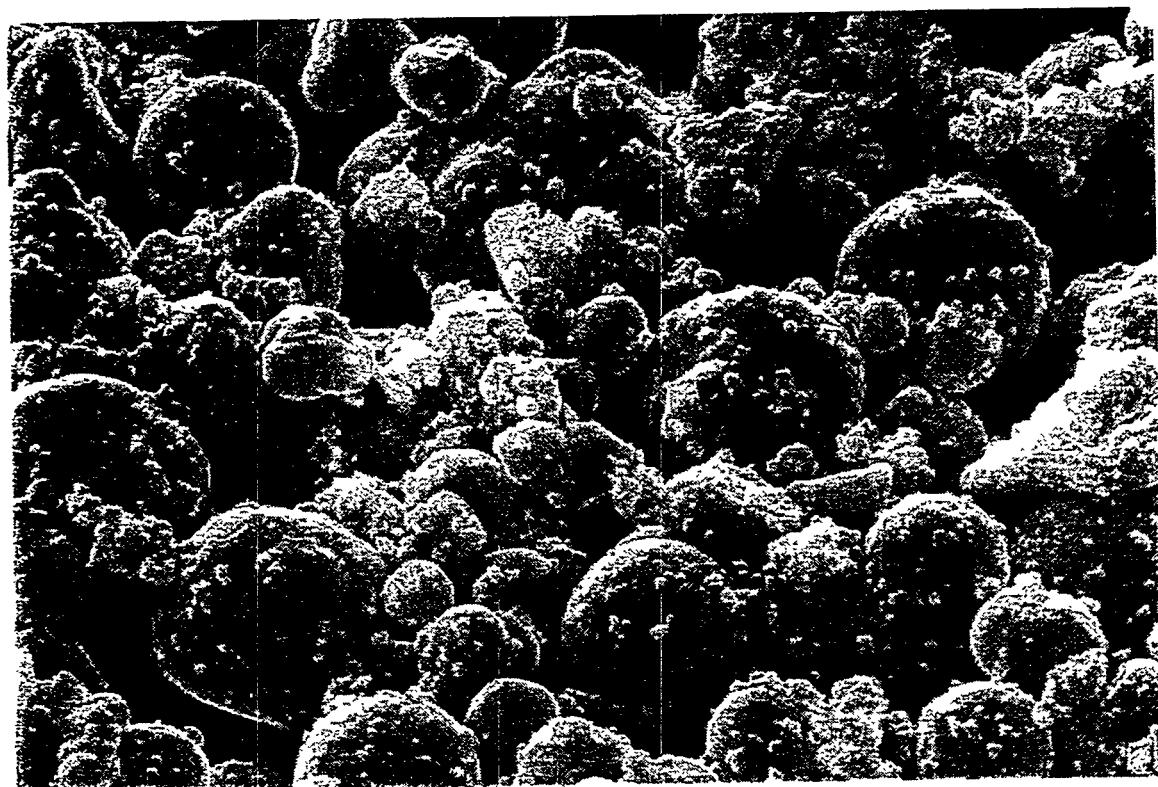
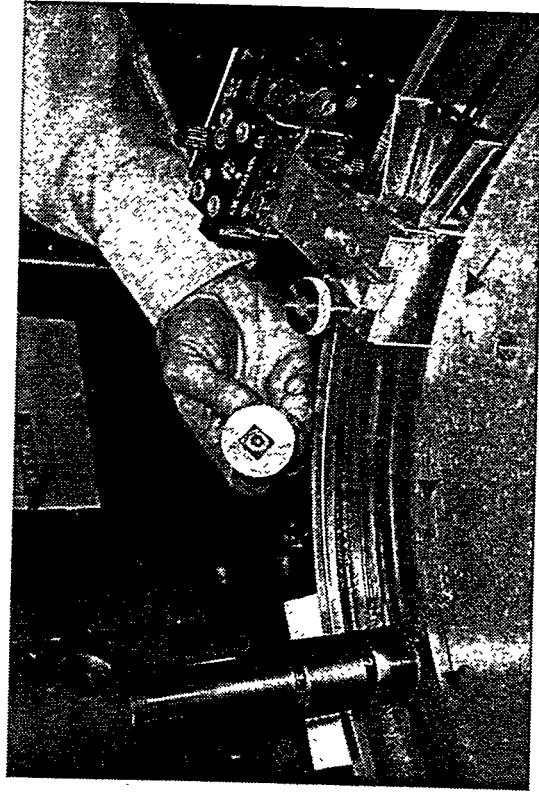


Figure 3

## Preprototype MRF Machine

- 10 rpm trough rotation
- 8 amp DC current to electromagnet
- 1.5 mm gap / 2 mm ribbon
- 30 minute contact with no part rotation

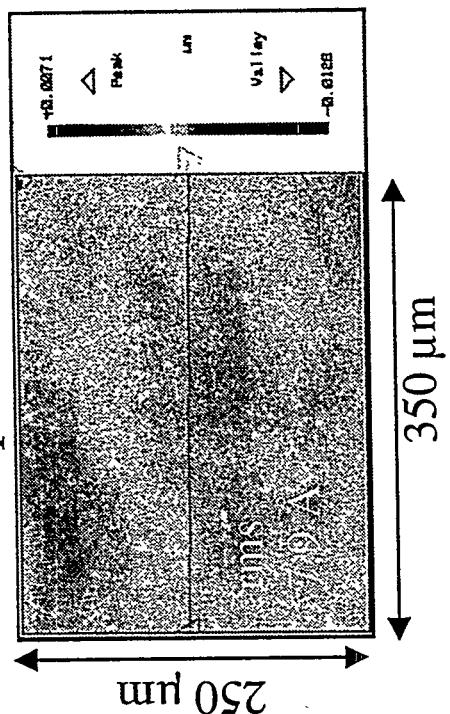


## Optical Glass Part

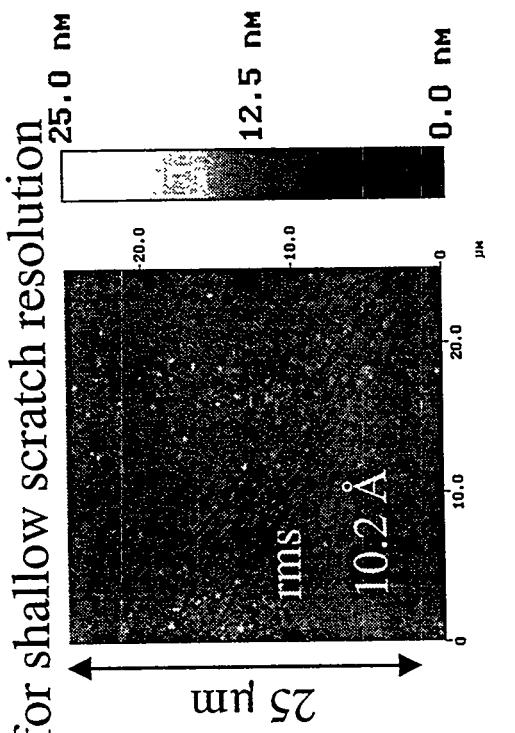
- Size: 1.2 cm diameter, .5 cm height
- Initial surface: flat to  $.06 \mu\text{m}$  p-v
- Initial roughness: pitch polished to  
 $\sim 8$  Angstroms rms surface roughness

Figure 4

Initial  
Pitch  
Polished  
Surface



Atomic Force Microscope



Surface  
After  
MRF

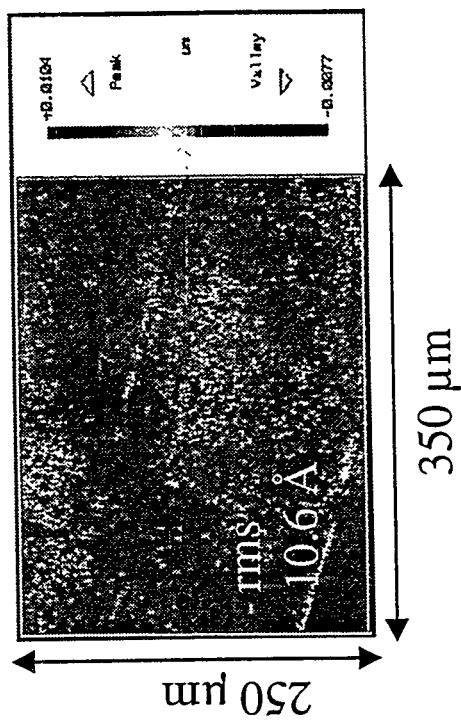


Figure 5

### Surface roughness achieved vs glass hardness using different types of CI

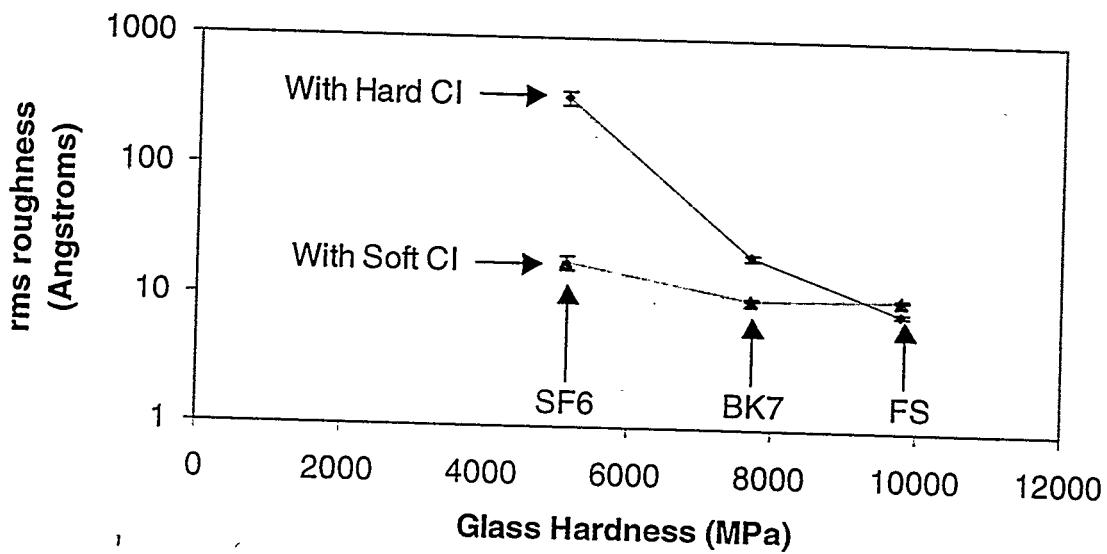


Figure 6

**Fused Silica**

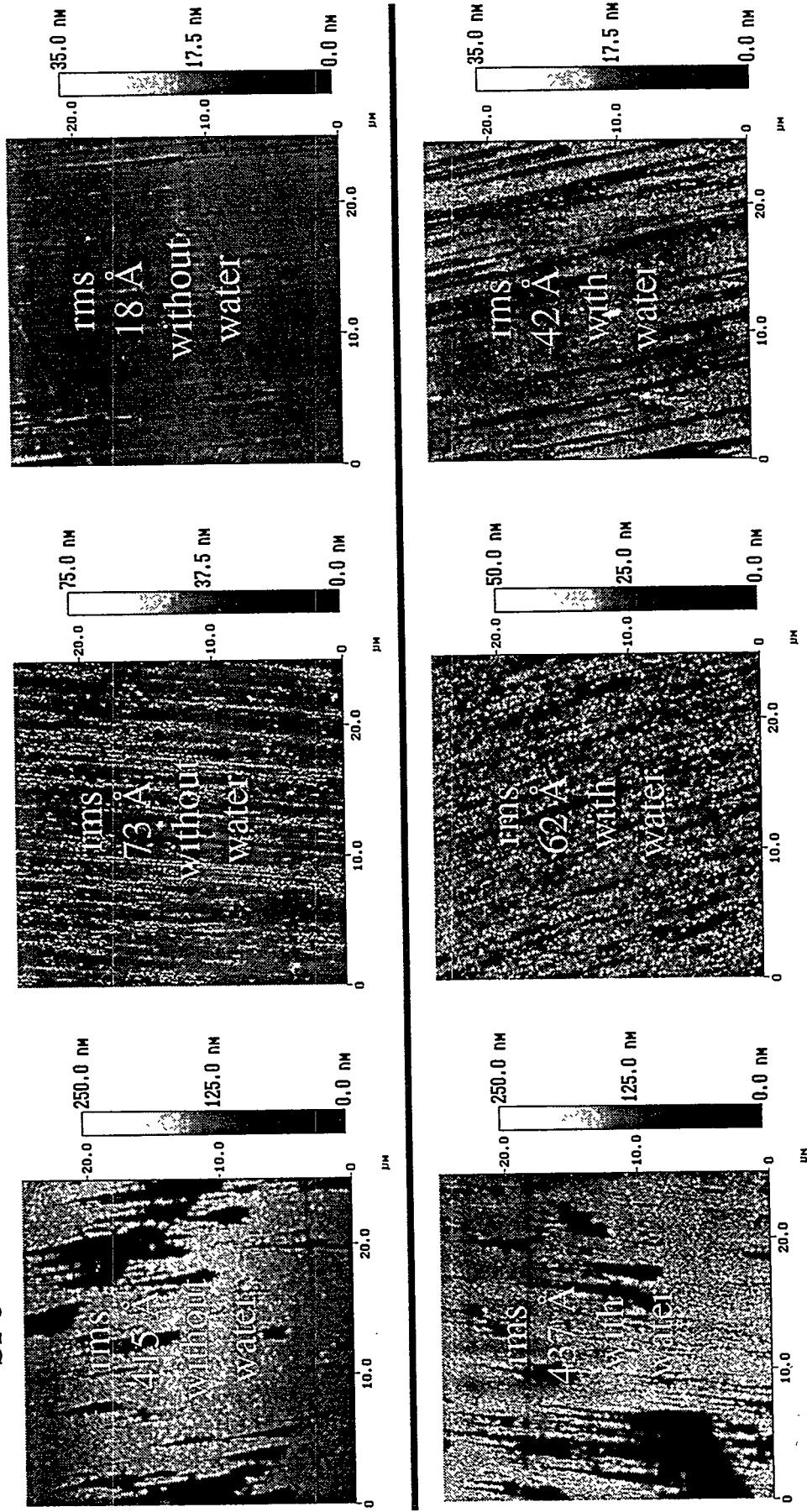


Figure 7

## References

1. QED Technologies, LLC, 1080 University Ave., Rochester, NY, 14607
2. Nano Indenter® II, Nano Instruments, Inc., Oak Ridge, TN 37830
3. Areal, 0.25 mm X 0.35 mm, 20x Mirau, Zygo New View® 100, Zygo Corp., Middlefield, CT 06455
4. Nanoscope III, Digital Instruments, Santa Barbara, CA

## Acknowledgements

I thank Aric Shorey for working closely with me on this project. Aric and Kevin Kwong obtained the hardness of the carbonyl iron particles. I would like to thank Henry Romanofsky who taught me how to use the preprototype MRF machine and the WLIM. Special thanks to Dr. Craxton for running this program. Finally, I would like to acknowledge my advisor, Dr. Stephen Jacobs, for his aid in organizing this project and for his assistance and support throughout the summer.

m.s. date 8-27-98