



Better Polishing through Chemistry

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Learning the chemical aspects of optical polishing can lead to better optics in less time.

Perfection is rapidly becoming the expectation in today's optics manufacturing market. More and more optical designers are demanding faster delivery and higher quality optics. At the same time, optical system engineers are facing shorter cycle times; they may be required to have a prototype designed, built, tested and delivered within a period of weeks rather than months. Standard eight-week or longer deliveries are not sufficient to meet the needs of the evolving industry. In addition, as new optical materials are developed and aspheric surfaces become common, greater optical manufacturing expertise is required to get the job done.

Traditional optical polishing involves using a polishing slurry of water and fine abrasive particles (e.g., cerium oxide) to rub against a viscoelastic material (e.g., polishing pitch) that is formed to a metal tool of matching shape to the optic. It is well-accepted that optical polishing is



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highly dependent on mechanics, specifically the relationship found by Preston, where removal rate is proportional to pressure multiplied by velocity.

The chemical aspects of polishing are also important. Choosing the proper slurry pH can increase polishing efficiency and improve the resulting surface roughness of optical components. Many optics manufacturers rely solely on their master opticians' artisan skills to produce their optics, but they should also consider analyzing their processes. Engineers who have knowledge of how chemistry and mechanics interact with the optical substrate will be able to give optics manufacturers better prediction models and manufacturing processes to accommodate the optics industry's expanding expectations and shrinking delivery schedules.

Theories on the chemical interactions of semiconductor chemical mechanical planarization (CMP) fill the literature.

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Cook was a pioneer in quantifying how chemistry affects traditional optical polishing. He found the relationship shown in Equation 1, in which MRR is the material removal rate, sbs is the single bond strength of the polishing abrasive, pH is the slurry pH and the IEP is the iso-electric point of the polishing abrasive (the pH of a host solution at which a particular surface/particle carries no net electrical charge).

$$\text{MRR} \propto \frac{1}{\text{Log}(sbs \cdot |\text{pH} - \text{IEP}|)} \quad (1)$$

According to Cook's equation, the slurry pH should be as close as possible to the IEP values of the polishing abrasives in order to maximize removal. When the slurry pH is close to the abrasive IEP, the abrasive particles will tend to agglomerate, and the resulting larger particles will increase removal rates. (For example, the IEP of cerium oxide generally ranges from 7 to 9, depending on the manufacturer, and the highest cerium oxide removal rates historically occur with near-neutral pH values.) Unfortunately, Cook's work did not account for changes in glass type, and he did not determine how this relationship affects the resulting surface roughness.

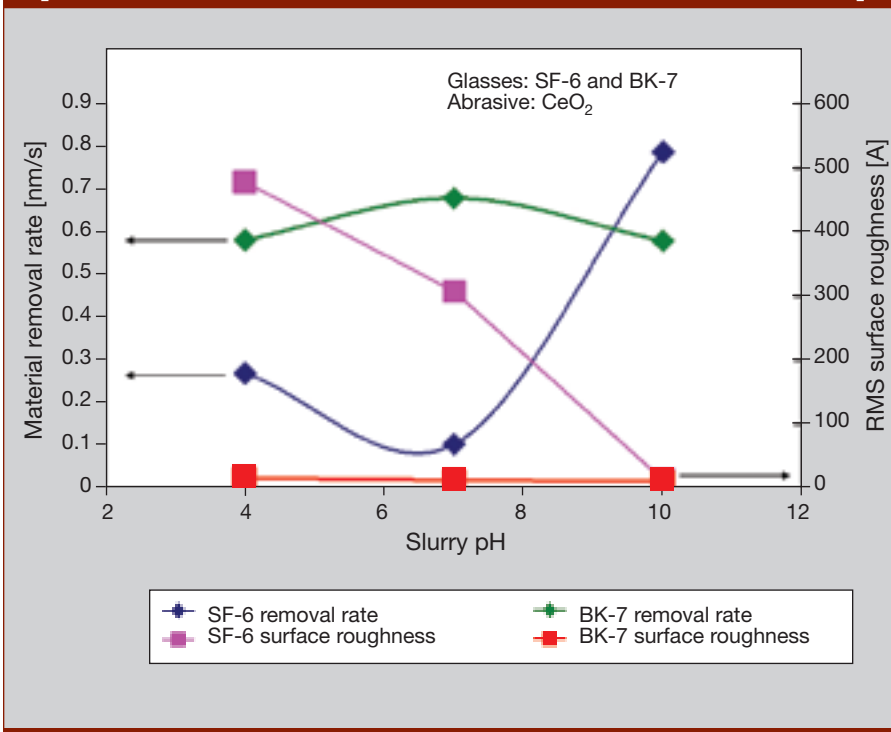
Cumbo extended Cook's work by studying how polishing slurry pH affects both removal rate and surface roughness. He found that the interaction between the slurry pH, glass type and abrasive plays a significant role in both the polishing efficiency and the resulting surface roughness. The figure on the following page shows his results for the borosilicate BK-7 and lead-silicate SF-6 polished with cerium oxide. Even though these two materials are both silicate glasses, their reactions to slurry pH are vastly different.

If one were to implement the results that Cumbo found for SF-6, a pH

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change from 7 to 10 would correspond to a 7-8× reduction in polishing time. Although Cumbo did not determine a quantitative relationship for removal rate and chemistry, he did coin the term "slurry charge control effect," which stated that the smoothest surfaces on silicate glass surfaces occurred when the glass surfaces and abrasive particles had repulsive electrostatic forces (same sign).

[BK-7 and SF-6 polished with cerium oxide in water at various pH values]



Even novel CNC polishing methods are not exempt from the effects of chemistry. My colleagues and I developed a model for predicting the material removal rate for magnetorheological finishing of glass (Appl. Opt. **46**, 7927-41). This model specified five terms associated with a number of mechanical and chemical aspects of the glass and nanodiamond magnetorheological fluid properties.

One of the terms focuses on the chemical durability of glass as a function of pH, where peak removal rate increases with a power relationship with decreasing chemical durability. A second term has an Arrhenius-like equation correlating peak removal rate to the bond strengths of the glass network formers. This indicates that glasses with weaker bond strengths will have higher removal rates than glasses with higher bond strengths. Both the material's chemical durability and bond strength can be determined before an optic is polished, so this information can help make polishing more predictable.

In current research, scientists are working with dozens of optical materials

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for applications ranging from ultraviolet (e.g., calcium fluoride and fused silica) to infrared (e.g., zinc sulfide and spinel) and many of the materials in between. This work has prompted a new wave of engineers and opticians to appreciate chemistry's role in optical manufacturing.

Chemistry's impact on polishing goes far beyond adjusting pH (e.g., treating abrasive particles to alter surface charge, salt concentration, non-aqueous fluids, etc.). For example, chemistry can be used to aid in the removal of hard materials such as polycrystalline infrared material aluminum oxynitride (AlON), which is used for dome and window applications and is very chemically durable. By

altering the chemistry of the fine grinding carrier fluid with non-aqueous fluid additives, AlON removal rates doubled. This process improvement has significantly lowered the total production time for AlON domes.

Although the experience and knowledge of master opticians is indispensable, it is not sufficient for every job. For example, imagine how frustrated your optician would be if you handed him or her a new optical material that requires a $\lambda/20$ -wave surface figure with less than 3 Å RMS surface roughness error on a rapid delivery schedule.

Now imagine this same scenario, but this time your optician has been trained on the mechanics and chemistry of grinding and polishing optics and taught how those factors can be used together to predict a more likely outcome. The probability for success is significantly greater.

Optics manufacturing will never be an exact science. But learning more about the effects of chemistry can help to make it a more refined art. ▲

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