Optics Become Less Rough, More Tough

Livermore chemist Rusty Steele (left) and principal investigator Tayyab Suratwala observe a workpiece being polished using the CISR (convergent, initial-surface-independent, single-iteration, rogue-particle-free) polisher. (Photo by Lanie L. Rivera.)

LIVERMORE'S National Ignition Facility (NIF), the world's largest and most energetic laser, uses more than 7,500 large optics to guide, reflect, and amplify its beams. The extraordinarily high energies produced by NIF make the sophisticated optics susceptible to life-limiting damage. Over the last decade, Livermore researchers have developed methods for producing highly damage-resistant fused silica (glass) optics (see *S&TR*, January 2015, pp. 19–22), yet these scientific investigators continue efforts to better understand and mitigate optics damage in support of NIF and its missions.

One feature of an optic that can influence damage initiation is its surface finish. Rougher optical surfaces scatter more laser light, which can affect the integrity of surrounding optics, reduce the quality of experimental data, and necessitate optics refurbishment or replacement. A Lawrence Livermore team, funded by the Laboratory Directed Research and Development Program, is investigating how surface roughness is created during the final polishing phases of fabrication. Examining the nanometer-scale chemical and mechanical processes that occur during manufacturing is crucial for identifying methods to further improve optics production.

From an Art to a Science

Standard polishing processes for glass optics use a slurry, an abrasive and corrosive aqueous solution that typically contains small polishing particles ranging from 1 micrometer to a few hundred nanometers. The slurry is used along with a polishing pad to smooth the optic's surface. "The physics and chemistry involved in making glass optics are quite complex," explains Tayyab Suratwala, Livermore's program director for optics materials science and technology. "The physical and chemical interactions that occur between the polishing agent and the pad with the optic, for example, occur simultaneously and affect the final product."

For hundreds of years, skilled laborers and opticians have used an artisanal approach to creating glass optics for scientific instruments, such as telescopes, microscopes, and lasers. Historically, opticians had to manually correct surface defects to create the smoothest surface possible. Although these traditional artisanal methods delivered high-quality products, they also required iterative steps, making the process time consuming and costly.

Over a decade ago, Livermore researchers developed a more science-based, streamlined approach to optics production by investigating three metrics of optical polishing: surface figure (overall optic shape), subsurface damage (scratches), and roughness. Through its work studying the first two metrics, the team developed CISR (convergent, initial-surface-independent, single-iteration, rogue-particle-free) polisher. CISR integrates a technique known as convergent polishing, wherein both flat and spherical glass components can be polished in a single iteration regardless of the workpiece's initial shape. (See *S&TR*, October/November 2014, pp. 8–9.)

Most optics' surfaces look perfectly clear and smooth to the naked eye, but in NIF's energy regime, the tiniest flaw—scratches or defects on the order of 1–2 nanometers—can affect laser performance. By combining simulations and experiments, the team aims to reduce defect sizes to 0.1 nanometers, making optical surfaces 10 times smoother than they are today. Suratwala says, "We are working to make a great optic into a spectacular one without added cost."

A Mysterious Layer

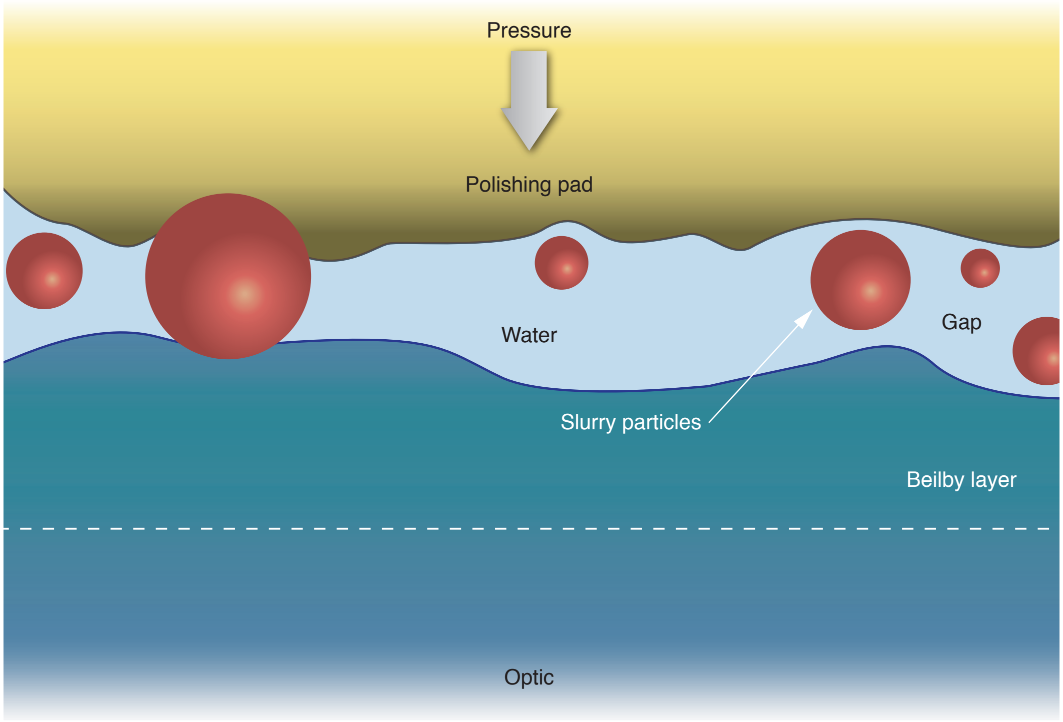
Years ago, opticians noted that a thin defect layer (approximately 0.7 nanometers deep), called the Beilby layer, forms in the surface of optics during polishing. The layer can cause subtle changes in light-reflection properties and can reduce the optic's resistance to laser damage. The Livermore researchers are the first to attempt to understand how the Beilby layer forms, what factors influence its thickness and composition, and how it changes over time.

The research team conducted experiments in which pieces of glass optics were exposed to slurries containing different chemical contaminants—concentrations of hydrogen and cerium, for example. The team discovered that the material properties of the Beilby layer constantly evolve throughout the polishing process because the chemicals in the slurry diffuse into and react with the glass surface. Ultimately, the team identified three primary materials in the slurry that affect the makeup of the Beilby layer: the polishing compound, alkali metal hydroxides (used to control the slurry's pH), and water. These new insights into the chemistry of the Beilby layer help develop a more quantitative understanding of the polishing process and how to reduce nanoscale surface roughness.

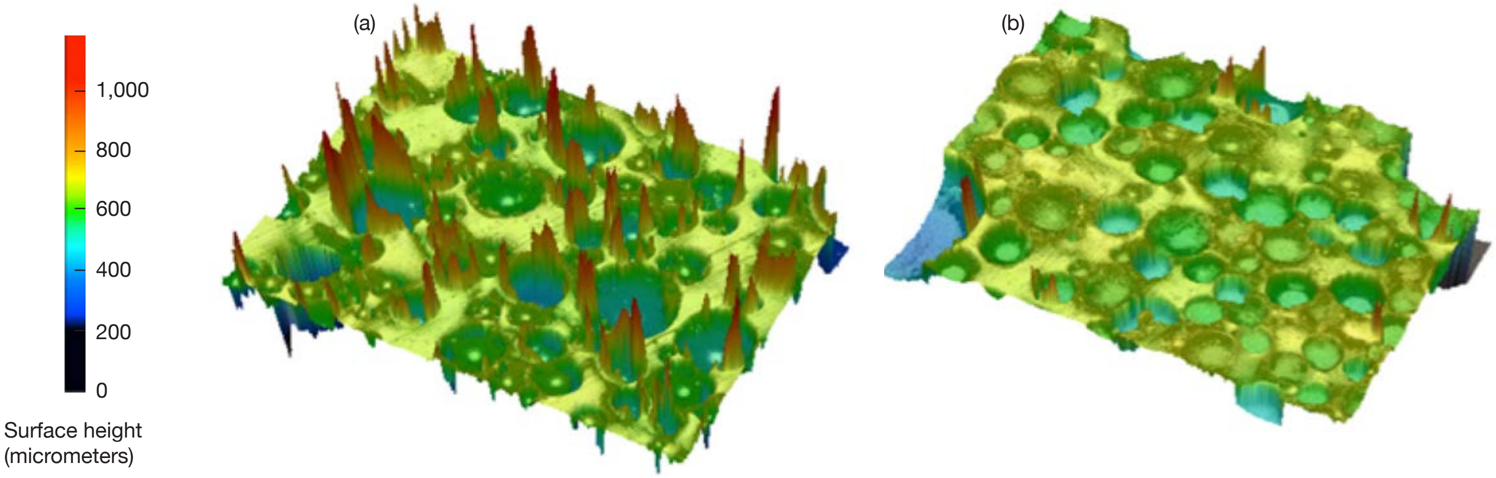
Scratching the Surface

As part of the team's simulation effort, the researchers created the Ensemble Hertzian Multigap (EHMG) model to study the origins and affects of nanoscratching on an optic. The model helps predict how much glass is removed by a single particle in the slurry, the removal rate, and overall surface roughness, given input parameters.

Optics polishing and particle removal processes are similar to using sandpaper. Coarser grit sandpaper quickly removes more material, leaving a rougher surface, whereas finer grit sandpaper lengthens the process but results in a smoother finish. However, when finer grit sandpaper is applied with greater pressure, surface material can be removed more quickly while retaining smoothness. Simulations showed the Livermore researchers that the same is true for optics polishing—surface smoothness depends on the size



The Ensemble Hertzian Multigap model simulates trends in observed roughness over a variety of polished surfaces. This schematic illustrates the relationships between the optic workpiece, Beilby layer, slurry particles, and polishing pad.

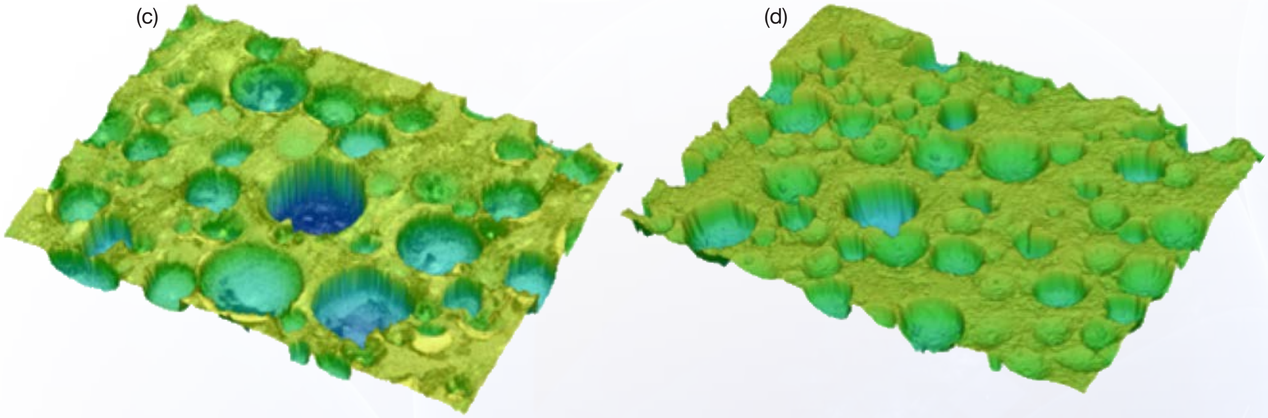


of the particles in the slurry and the pressure applied between the polishing pad and the optic.

To inform the EHMG model, the team conducted atomic force microscopy experiments to examine the surface characteristic of different polished optics and visualize how individual particles affect surface roughness for various particle sizes and loads. In this technique, an extremely sharp probe tip attached to an atomic force microscope senses the surface shape of a sample. A computer records the tip's path and slowly builds up a three-dimensional image. Suratwala says, "We used the microscope to mimic the pressure a particle would experience during optics polishing to see how much material is removed from the substrate through nanoscratching."

The experimental data was incorporated into the model, which simulated one particle at a time sliding across the optic's surface. The process was repeated for hundreds of thousands of different particles with varying sizes under applied pressures, until the final surface roughness was reached. The simulations indicated that the amount of material removed per slurry particle and the particle load distribution are key factors influencing an optic's surface roughness.

Livermore optics scientists (from left) Nan Shen, Lana Wong, and Rebecca Dylla-Spears examine an optic prior to imaging its surface. (Photo by Lanie L. Rivera.)



Confocal microscope images show the surface characteristics of the polishing pad (a) before and (b) after polishing an optic. The team's modified diamond-conditioning treatments lasting (c) 5 minutes and (d) 45 minutes reduced tall asperities on the pad surface and increased its overall smoothness. By applying the smoothest pad to an optic with more pressure, surface removal rates increased from 0.08 to 2.1 micrometers per hour.

Pad Plays a Part

Polishing processes conducted in optics-related industries often apply diamond conditioner to used polishing pads to remove the film of glass particles (called "glazing") that accumulates on a pad's surface during the polishing process and reduces its efficiency. In some cases, as in the semiconductor industry, pads must be constantly conditioned to remove the excess glass, but with each subsequent conditioning, the pad becomes rougher and its useful life is reduced. "The diamond wears down the pads enough that they usually have to be thrown away after a few hundred hours," says Suratwala.

The Livermore team took a novel approach to diamond conditioning and discovered that, under certain conditions, the procedure could be modified to make the pads smoother rather than rougher. The researchers used the diamond conditioner only once to remove glazing spikes on the pad's surface. Then, they applied an ultrasonic cleaning method where gentle vibration and water shake loose any residual glass from the pad. "Using this process, the pad remains flat, the glass is quickly removed, and roughness is reduced," says Suratwala. The team also found that by applying the smoother pad to an optic with greater pressure, polishing time was significantly reduced. The surface removal rate accelerated from 0.08 micrometers per hour without the conditioning treatment to 2.1 micrometers per hour after treatment. "Our polishing pads remove more material faster and last for thousands of hours."

With the team's insights into how a pad's surface characteristics, nanoscratching, and the Beilby layer affect optics quality, Livermore remains at the forefront of optics polishing research. "These major findings are unique and influential to the optics polishing industry," says Suratwala. A second-generation CISR, to be finished this year, will incorporate the team's most recent improvements for increasing surface smoothness. Once the team fully integrates its process optimizations into current polishing methods, the Laboratory and the optics industry will have a new tool for creating the clearest, smoothest optics available.

—Lanie L. Rivera

Key Words: atomic force microscopy, Beilby layer, CISR (convergent, initial-surface-independent, single-iteration, rogue-particle-free) polisher, Ensemble Hertzian Multigap (EHMG) model, Laboratory Directed Research and Development Program, nanoscratching, National Ignition Facility (NIF), optics polishing, polishing pad.

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