Aspheres can be polished using magnetorheological finishing, a deterministic technique. Image courtesy of Edmund Optics.

# Polished to perfection

**Greg Blackman** investigates some of the advances made in the polishing and finishing technology employed in optical fabrication

The processing steps involved in optical fabrication are many and varied but, put simplistically, things generally start with a lens blank that is then ground and polished to its final form. Polishing is typically through a lapping process, which involves rotating and rubbing the lens against an abrasive tool and, using feedback from metrology data, gradually working it to achieve the desired shape. It is then cleaned and coated.

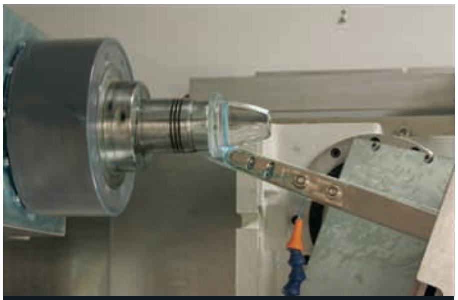
Conventional slurry polishing, a chemical/mechanical polish in which a slurry containing abrasive particles flows between the optical surface being polished and a pad, is still used by many manufacturers. The optic is typically mounted on a block and this assembly is floated on top of a pad with a tailored viscosity. The slurry will usually have a specific pH to generate a slight etching of the surface and this combined with the suspended abrasives removes material from the part.

This technique is fairly standard and has been around for many years. Some advances have occurred through use of the metrology techniques now available to measure the surface finish of a lens during the polishing process. This is according to Nick Traggis, vice president of photonics at optics manufacturer Precision Photonics, who says: 'Coupling this [conventional slurry polishing] with high-end metrology capabilities to provide feedback to the operator is one of the biggest advancements Precision Photonics has brought to its manufacturing.' He adds: 'If you can't measure to a specification then there's no way that you can develop a process for it. Our push is the ability to measure things better than our customers or competition.'

Among the polishing capabilities employed by Precision Photonics is spindle polishing, in which the block is attached to an arm that introduces a pattern over the top of the polishing pad while the slurry is flowed between the part and the pad.

The company also uses double-sided polishing, in which the parts are floated between two large plates with the top and bottom surfaces polished at the same time. For this technique, Precision Photonics has developed an interferometric metrology tool based on an ultra-stable laser. This allows a piece of glass to be measured to a thickness of better than a tenth of a nanometre.

By combining double-sided polishing with the interferometric metrology tool, the company can polish a three-inch diameter wafer to less than 10nm thickness variation across the entire three inches. 'It's an almost perfectly parallel substrate from one end to the other,' explains Traggis. 'We use this for things like etalon fabrication, which is a commodity component used in telecommunication devices. We ship tens of thousands of these overseas every month and the reason we're able to compete with Asian suppliers is that we have this metrology advantage coupled with strong polishing capability. This allows us to polish a larger wafer and essentially have a higher yield per lot effort to



Polishing on OptiPro Systems' UltraForm Finishing (UFF) machine designed for aspheric and freeform optics.

remain cost-competitive. That's a great example of being able to compete on a commodity product, because we have technological advantages in our optics fabrication.'

### Superpolishing

Precision Photonics also has superpolishing capabilities to achieve a very smooth finish at sub-angstrom roughness levels (an angstrom is $10^{-10}$m, or 0.1nm). While a typical commercial optical polish would have a surface roughness in the range of 5-6Å RMS, a superpolished surface has roughness levels of less than 1Å RMS. To do this, the company uses continuous polishing with a large, single-sided machine.

For superpolished optics, the metrology feedback to the operator becomes even more crucial. 'When polishing a superpolished optic to a roughness of less than 1Å RMS across the surface, you have to be able to measure to that level and there are very few companies in the world that can do that,' comments Traggis.

Precision Photonics has developed a measurement system, based on a Nomarksi microscope, to measure these surfaces. 'We're measuring light scattered from the surface and referencing that against a standard to calibrate the equipment to sub-angstrom levels. And this is for the same pitch polishing that optics manufacturers have been using for hundreds of years, just with advanced metrology equipment,' Traggis says.

Surface roughness is an important factor in a lot of optical applications in terms of the scattering of light. The rougher the surface the more randomly scattered light there is and that scattered light represents lost light; it represents a weaker signal and greater noise.

Having a level of roughness of less than 1Å RMS is not important for all applications, but there are certain applications where it's vital – in ring laser gyroscopes, for instance, which are often used in aerospace and military applications as part of advanced guidance systems. Optics manufacturer Gooch and Housego produces superpolished mirrors for these devices. 'It's really a process that's important for some advanced equipment to operate,' states Dick Neily, engineering manager at Gooch and Housego. The company has also provided superpolished mirrors for the Mars Rover, again, as part of a guidance system.

'We're trying to polish the mirror to such an extent that it becomes almost a perfectly smooth surface, a perfect reflector, so that all the light that hits it reflects off in a predictable direction, rather than being randomly scattered,' says Neily.

Superpolished transmissive optics are less common, notes Neily, but there are requirements for these, such as in resonating optical cavities, where the light is passing through the optic multiple times. Even though the optic may have an antireflection coating, if the roughness is too great, each time the light passes through the optic there will be a certain amount of scatter, which can degrade the performance of the cavity.

### Polishing aspheres

Conventional polishing techniques are still widely used and Traggis of Precision Photonics (the company's focus is on prismatic assemblies and planar optics) says that some of the newer polishing techniques, which he admits do have a place in the industry, don't provide as good a finish as some of the conventional techniques. 'Although we have evaluated the newer technology,' he says, 'the conventional polishing combined with metrology techniques that tune the process give better results.'

Magnetorheological finishing (MRF) is one of the newer deterministic polishing methods (relative to slurry polishing that is, although it has been around for more than 10 years) and, according to Traggis, one which, while not suitable for the planar optics manufactured by Precision Photonics, does work very well for optics like aspheres and other spherical-type surfaces.

MRF is a polishing technique that uses a magnetorheological finishing slurry, the shape and stiffness of which can be magnetically controlled in real time throughout the process. The machinery shapes the optic according to data inputted, which is interpreted by computer algorithms. Through the software the machine knows how long to dwell in each area, how fast to rotate the part, how fast to send the ribbon over the wheel, etcetera, in order to polish the part.

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Edmund Optics employs QED MRF polishing machines along with sub-aperture pad polishing to fabricate its aspheres. 'With MRF polishing, there's really no user input once the part is in the machine,' explains Nicholas Smith, manager of asphere lens fabrication at Edmund Optics. 'The downside to that is the technique is only as good as what you put into the machine – if you're trying to polish a really bad part it will take a long time. Therefore, the sub-aperture polishing is used to achieve a good finish and then the MRF equipment polishes it to a higher quality finish if required.'

## CNC-based polishing

Deterministic computer numerically controlled (CNC) processes are now widespread in optics fabrication and provide advantages over conventional methods in terms of shorter processing times and cost-effectiveness for manufacturing small batches. UK company Laser Components uses CNC-based polishing to fabricate its optics for mid- to high-power laser systems. Used in combination with interferometers, the process achieves substrates with λ/10 surface flatness as standard or possibly higher, up to λ/20.

'There are still a lot of companies that fabricate and polish optics by hand and achieve λ/10 flatness,' comments Bernhard Russell of Laser Components. 'However, the advantage with using CNC grinding and polishing machines is speed. In theory, we can grind and polish a substrate and deliver it within a day, although standard delivery times are typically two to three days.'

Optics company Research Electro Optics (REO) has also installed CNC optics fabrication machines at its site in Colorado, US to increase production speed. Rapid prototyping and low volume production demand has driven the necessity for this, according to Mark Damery, vice president and general manager of worldwide sales at REO.


**In CNC polishing, components are rapidly processed one at a time. The entire process takes about five to 10 minutes per part.** Image courtesy of Research Electro Optics (REO).

'The optical fabrication technologies we have as our foundation go back to traditional spindle polishing, which is the basic method for fabricating flat and spherically curved optics,' Damery says. 'We have hundreds of spindles and employ them on a wide variety of optics. However, this technology has its limitations. You can make one-inch diameter optics on a spindle and you can make lots of them, but it doesn't take away the fact that the polishing cycle is more than eight hours in duration per side. CNC polishing, on the other hand, takes between five and 10 minutes per part.'

Both Laser Components and REO are manufacturing optics for laser systems, which can be subjected to intense energy fluencies. For the coatings to adhere properly to provide good damage threshold, the substrate needs to be polished to a high level of accuracy in terms of scratch-dig (an assessment of optical quality) and flatness. Both Laser Components and REO can achieve a scratch-dig of $10^{-5}$ with their CNC-based polishing machines.

## Freeform optics

Moving from polishing rotationally symmetric aspheres to polishing freeform optics is still considered a big step and, as with all of these processes, the challenge lies in accurately measuring the surface shape. 'There are various solutions available that can measure aspheres, such as computer generated holograms (CGH) or profilometers,' explains Mike Bechtold, president of OptiPro Systems, a manufacturer of optical fabrication equipment. 'However, there are not many solutions for measuring freeform optics and one of the big challenges, as yet unsolved, is to measure a freeform optic to optical tolerances.'

OptiPro is working on this with its UltraSurf non-contact, five-axis, scanning system used to measure aspheric and freeform optics. In addition, the company's UltraForm Finishing (UFF) machine, a high-precision belt polishing system, is designed for aspheric and freeform optical polishing.

'Optical tolerances are measured in light waves, in angstroms, which relies on non-contact methods,' states Bechtold. 'Interferometers work well with spherical and plano optics, and CGH measurements can be used with aspheres, but the fringes are distorted when measuring a freeform optic too quickly.'

Bechtold adds that contact measuring methods are not accurate enough: 'Even with the most advanced coordinate measuring machines (CMM), positioning the probe or the part both involves error, typically larger than the total optical tolerance. Being able to measure these freeform shapes is still the holy grail, if you will, and there are currently no commercial solutions available to do this.'

The UltraSurf machine has 200 x 200 x 200mm xyz motion with two high-precision rotary stages (0.07 arc second accuracies). The linear stages are air-bearing and can position to 25nm accuracy. 'The system positions the components as accurately as possible but there are still errors involved,' comments Bechtold. The system is precise from the positioning side and a variety of optical probes are available providing accuracies of better than 1µm.

One of the more common types of freeform components is an off-axis asphere, which is fabricated from a segment of a parent rotationally symmetric asphere. Ed Fess, engineer at OptiPro, says: 'A lot of the time, the segment chosen is far enough off-axis that the traditional manufacturing methods of producing the rotationally symmetric parent are unusable because the parent part would have to be so big to make the segment.' These optics are raster-ground and raster-polished.

A lens that conforms to the leading edge of an airplane wing and therefore doesn't have any rotational symmetry is another example of a freeform optic. The optic has to conform very accurately to the shape of the wing for aerodynamic purposes. 'This therefore wouldn't be a rotationally symmetric shape but it would still need some level of optical accuracy,' says Fess.

There have been many advances in polishing and finishing, not just in the metrology technology available, but also in the machine components, which have helped to minimise the error and make positioning more accurate, and in the computing power now available, which has allowed optics manufacturers to play with the idea of generating new optical freeform shapes. Bechtold concludes: 'The algorithms developed for optics fabrication are crunching a lot of data. It's really only been in the last 10 years that the computing power to model these freeform optical systems has been available. Now we're playing catchup in terms of grinding, polishing and measuring.' ●