A Smooth Optical Surface in Minutes

Zeeko's modeling of fluid jet polishing (FJP) has enabled some of its major clients to replace the hand finishing of ultra-precise optical components with a machine process of higher quality that takes a fraction of the time.

BY JENNIFER HAND

Milling, grinding, polishing and finishing: the manufacture of high-quality products such as space telescopes, orthopaedic joints and digital cameras involves a number of precision processes either applied directly to glass or metal, or indirectly to a mold. Whichever method is used, the key requirements are a completely smooth surface and global form accuracy of only a few nanometers. In some cases the only option has been to finish components by hand, a time consuming and highly labor intensive operation.

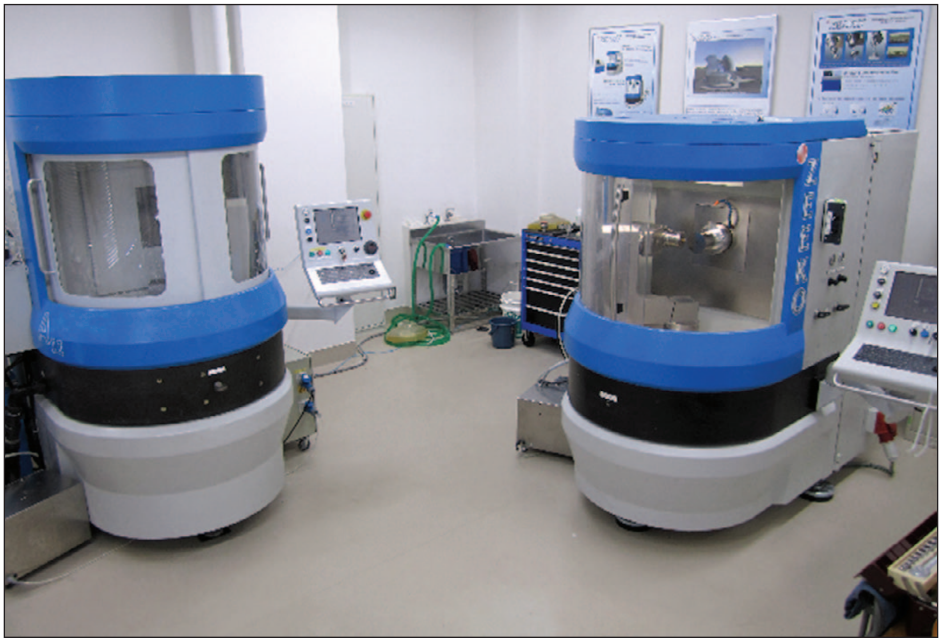


Figure 2: The Zeeko Intelligent Robotic Polisher. The position and pressure of the FJP tool are controlled by the Zeeko 7 axis CNC (Computer Numerical Control) machine tool controller.

Looking for a More Efficient Method

Zeeko Ltd is a UK-based technology company that manufactures corrective polishing machines. Its ultra-precision polishing solutions are being used in the development of the European Extremely Large Telescope and the Thirty Meter Telescope to be sited in Hawaii. Dr. Anthony Beaucamp of Zeeko describes the search for a new technology to deliver a higher quality than hand finishing. "There has been a lot of interest in the potential of fluid jet polishing, which pumps a mixture of water and abrasive particles through a nozzle onto a workpiece. This has significant advantages: the footprints generated can be less than a millimeter and it works with a wide range of materials. It can also remove machining marks from prior processes without introducing another tool signature and there is no issue with tool wear."

In the context of optical components, however, there was one significant problem. Despite research by a number of parties, the end result using FJP was always a surface with quite significant waveforms. "A small amount of waviness is generally acceptable; however, certain mid- and high-spatial frequencies can cause light scattering, optical deformation or even diffraction," comments Beaucamp. "Unfortunately surfaces polished by FJP generally featured more than 10 nm Ra of such waviness — far too much." Ra (Roughness Average) is the arithmetic mean of surface measurement maps.

Although this problem had been known since the late 1990s, Dr. Beaucamp was determined to find a way through. In 2010 Zeeko established a research centre at Chubu University, Japan, where they installed a CNC machine equipped with FJP technology (Figure 2).

With some initial support from Kesco Engineering in Tokyo, Dr. Beaucamp and the university team began to develop a computational fluid dynamics (CFD) model to investigate a number of the characteristics with FJP. In particular, they wanted to simulate the interface between fluid and air and trace the trajectories of individual abrasive particles. They then intended to compare the results achieved through modeling in COMSOL

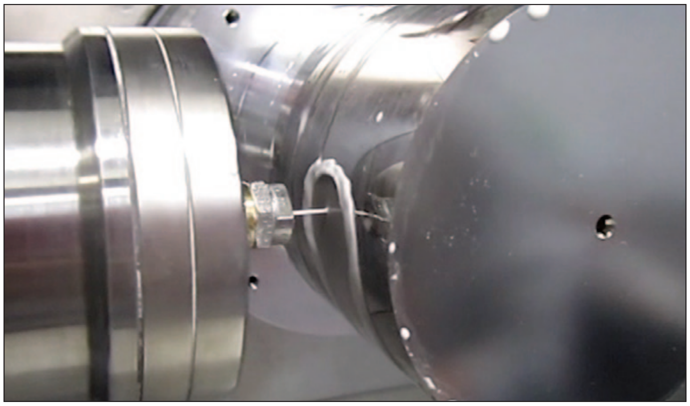


Figure 1: Fluid jet polishing of an aspheric die for thin X-Ray mirror replication. See the video at www.comsol.com/video/337/.

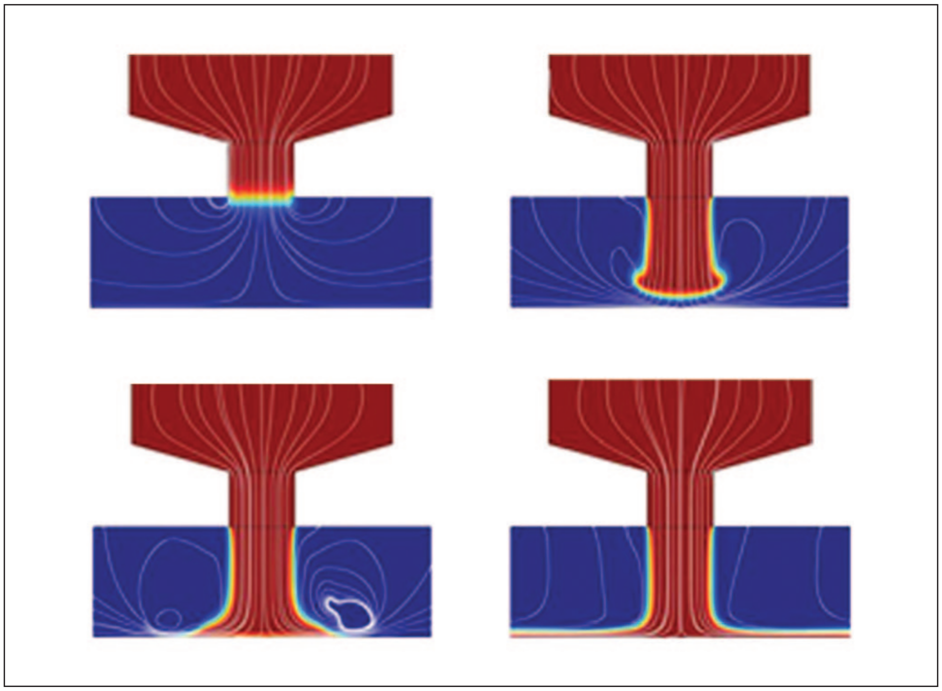


Figure 3. Snapshots of simulation: slurry (red), air (blue), and streamlines (white).

Multiphysics with actual machine performance. “Our aim was to get as close to 1 nm Ra as possible.”

Multiphase Modeling

“In FJP the jet forms a little spot that moves on the surface,” explains Dr. Beaucamp. “The spot follows a very tight raster path covering the optical area. The pumping system influences the jet pressure during this motion and it is the combination of pumping and tracking that results in waviness. In terms of setting boundary conditions, the main thing was to understand resonant frequencies within the impinging flow from the nozzle, and how changing those frequencies would affect machining.”

The first stage was to model the fluid in a time-dependent state, flowing from the nozzle, impacting the surface and then flowing away. The simulation used the k-ω turbulence model together with level set and phase field methods to model the fluid-air interface, and produced a series of chronological snapshots (Figure 3).

Further, the team did not want to assume that the particles within the slurry were ‘entrained’ or followed the fluid streamlines, so actual particle trajectories were also simulated (Figure 4). To do this, Dr. Beaucamp used the Particle Tracing Module, with Newtonian formulation to consider forces on the particles, like drag. The model showed a boundary layer that could only be penetrated by particles greater than 100 nm in size. Yet, it also indicated that the removal mode must be ductile (i.e., elastic) as particle energy was quickly dissipated over very small areas of the surface. This was also seen experimentally as no evidence of permanent damage, such as scratching or scouring, was evident.

Being confident with the model, Dr. Beaucamp could start using it to optimize the waviness that is primarily due to pressure instability in the slurry delivery system. Here, the nozzle was originally comprised of a high-pressure diaphragm pump and pulsation dampener. This resulted in progressive pressure drift (Figure 5, blue curve) so in order to improve inlet pressure stability, the team added a low-pressure feed-in pump to the system and connected a pressure gauge to the inverter powering the pump. This estab-

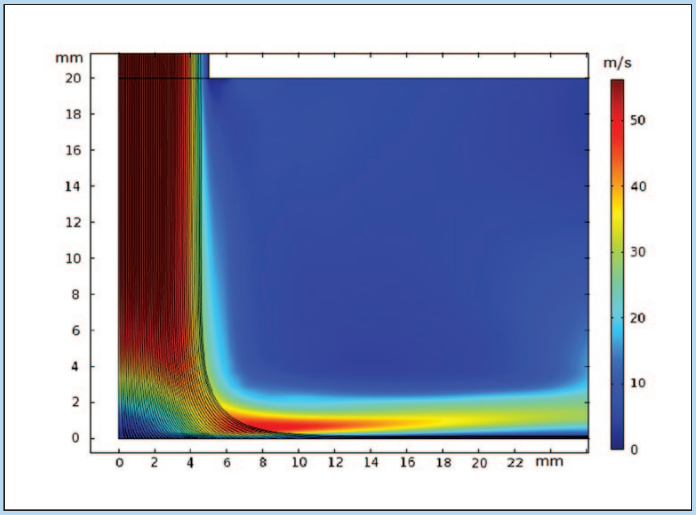


Figure 4: Particle tracing (black) and fluid velocity in m/s (color scale). The figure shows where the boundary layer (dark blue in color) is.

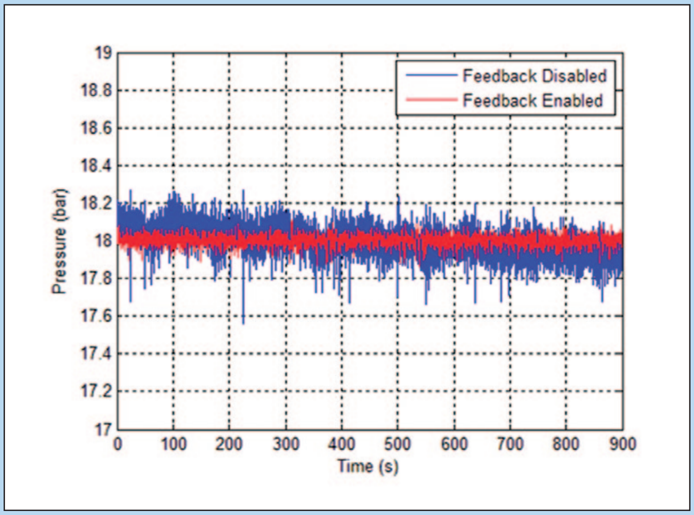
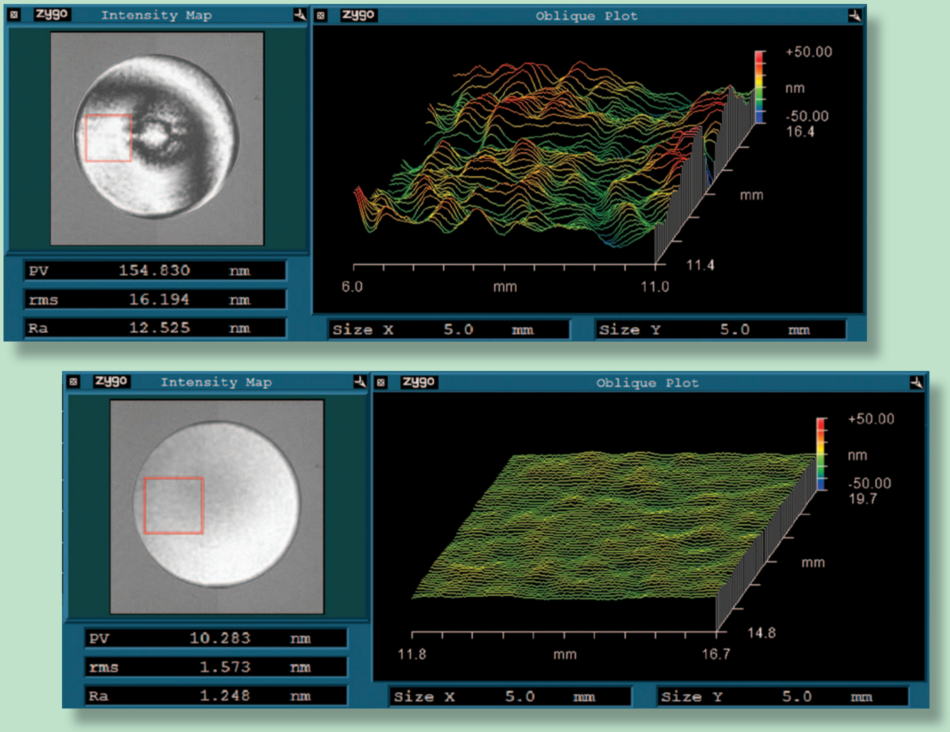


Figure 5: Pressure stability with (red curve) and without (blue curve) a feedback loop. Use of the feedback loop basically nullifies pressure drift.



PV 154.830 nm
rms 16.194 nm
Ra 12.525 nm
Size X 5.0 mm
Size Y 5.0 mm

PV 10.283 nm
rms 1.573 nm
Ra 1.248 nm
Size X 5.0 mm
Size Y 5.0 mm

Figure 6: Surface roughness on 5 × 5 mm area of BK7 glass: (top) before optimization and (bottom) after optimization. The optimized operation reduced Ra from 12.5 nm to 1.2 nm, while the fringe map (left) clearly indicates the eradication of the waviness.

Figure 7: The new integrated system, which has a footprint less than a quarter of the size of the laboratory machines used for research.

lished a feedback control loop that improved overall pressure stability and corrected the average pressure drift (Figure 5, red curve).

From the results given in Figure 5, Dr. Beaucamp could predict the underlying pattern of pressure variations, imposed by the pump, through using Fourier transform analysis. Here, they could characterize the slurry system in different states and include these pressure patterns in the COMSOL model. The model was then used to compute optimal conditions for the slurry delivery system using various nozzle sizes, stand-off distance and slurry types. Parametric sweeps were run and variations in the removal footprint extracted and analyzed. By examining trends in these variations as well as other results within the model, Dr. Beaucamp could recommend a number of optimal running conditions dependent on the piece being machined, and the material it is made from.

"A hand process that could take more than one day is now accomplished in ten minutes."

From the Model to Mechanical Set Up

Once Dr. Beaucamp's team had reached a set of operating conditions the model described as being optimal, they then carried out experimental comparisons to gain confidence in their method. They did this by polishing optical grade fused silica glass windows under both their original and then the optimized slurry delivery system conditions. The surface roughness was measured with an optical profiler and white light interferometer. Using software from Zygo Corporation, plots of the roughness and its intensity were given, along with the Ra value (Figure 6). "As we had anticipated, the non-optimized system showed a large amount of waviness over a 5 × 5 mm area (12.5 nm Ra) whereas this was greatly improved in the optimized system (1.2 nmRa)," he reports.

From One Day to Ten Minutes

Once Dr. Beaucamp and his team had the results they were seeking they lost no time turning them into an industrial application (Figure 7). Zeeko developed a production version of the research equipment and began selling it in Japan.

A number of major Japanese and Korean manufacturing companies are now using Zeeko technology for finishing optical molds. "A hand process that could take more than one day is now accomplished in ten minutes," explains Dr. Beaucamp. "This is giving our customers a huge advantage, enabling them to make better products and cut production costs. Until this breakthrough they were relying on very experienced optical workers to polish by hand; they simply could not get a machine to do this." ■

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