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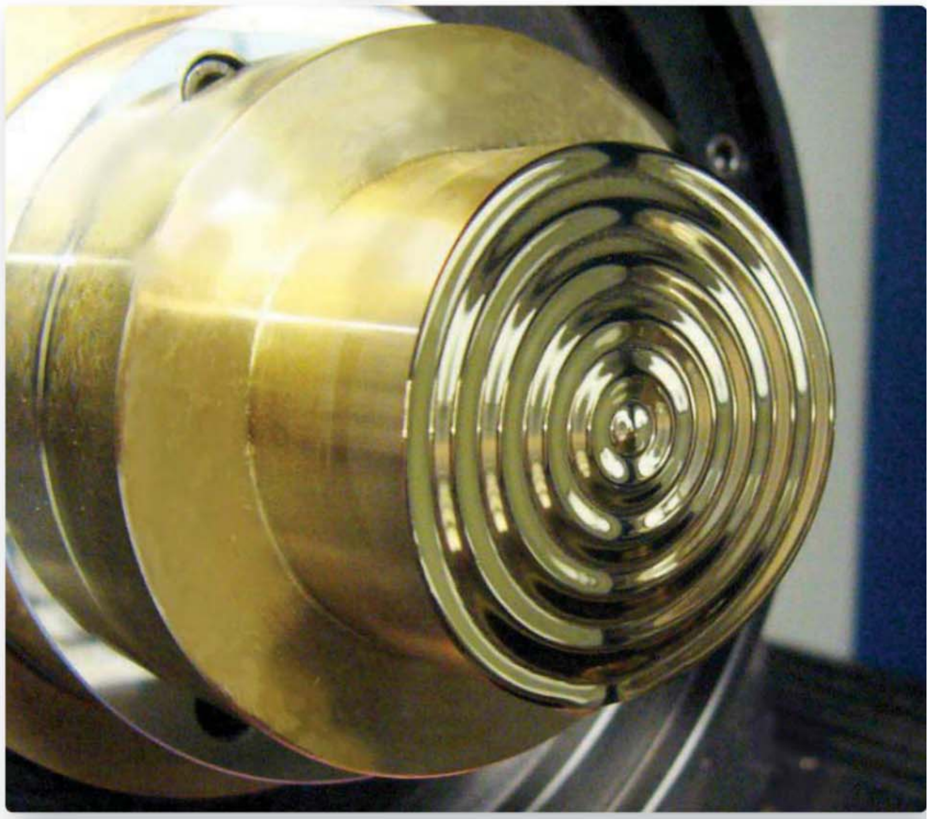
Viewing Instructions

Fundamentals of ultraprecision machining

It no longer takes exotic machining to hold submicron tolerances.



Ultra Precision three-axis diamond turning creates a toric with a sine-wave pattern in brass. Final surface is produced without postpolishing.

Ultraprecision machining (UPM) comes from the optics industry so not many designers are familiar with the process. However, the technology has the potential to revolutionize the way manufacturers, in general, finish parts or make fine-featured patterns.

First, recall that "high precision" in traditional machining generally refers to tolerances in the single-digit micron range. In inch units, machinists talk about holding "tenths" (ten-thousandths of an inch, or 0.0001 in.). And the best conventional machining and grinding machines typically get Ra values no better than 0.1 μm. In contrast, ultraprecision machining provides accuracy an order of magnitude better by holding submicron tolerances. UPM also obtains surface finish Ra values better than 0.5 nm. When using diamond tooling on nonferrous materials, UPM produces yet more-impressively smooth finishes.

Ametek Precitech, in Keene, N. H., manufactures UPM equipment and has provided the benchmark for this technology. Precitech's machine layout resembles that of standard equipment, but the details make all the difference. Programming input resolution, the precision level of the machine inputs, is 0.01 nm for linear and 0.026 arc-sec for angular position. Workpiece spindle speeds hit 18,000 rpm and milling spindles rotate at 15,000 or 50,000 rpm. Workpiece positional accuracies of 1 micron linear and ±2 arc-sec are standard and — because these errors are repeatable — software compensation can be used to reduce them by a factor of 10.

The company's machines have a solid foundation made with a sealed granite base that provides physical and thermal stability. Mounted on pneumatic isolators, the base remains protected from external excitation including footfalls, road traffic, and nearby mechanical equipment.

In addition, the UPM machines have an axis stiffness as high as 875 N/μ as well as Adaptive Control Technology (ACT), which analyzes feedback, including disturbances. ACT also provides active cancellation (analogous to noise-canceling headsets) that continually

Ultra Precision diamond turning is used to form a pivot bearing on an electroless-nickel-plated toric form with a surface accuracy better than 70-nm peak to valley (PV).

Ultra Precision two-axis diamond turning creates a diffractive, infrared lens of germanium. Final surface is produced without postpolishing.

adjusts and fine-tunes system-control parameters. The critical element is the anticipation of a repetitive event such as a resonance and the preemptive application of compensation. The machines feature onboard metrology as well.

What's more, the UPM machines use only air and oil bearings to eliminate mechanical interactions of surfaces. This means that friction all but disappears.

In traditional machining, coolant handles heat generated at the workpiece but heat generated by the machine itself is ignored. UPM equipment is itself liquid cooled, adding the necessary dimensional stability to maintain accuracy and repeatability. Chillers are used to cool spindles, slides, rotary tables, and other moving parts to insure dimensional stability, remove heat from cutting tools, and prevent heat transfer to structural elements.

Ultraprecision machining can be performed via turning or freeform machining. With turning, the machine generates rotationally symmetric geometries. With freeform machining, the machine generates complex geometries based on an *X-Y-Z* coordinate system. Freeform machining can be further divided into Servoform 3D or Fast-Tool Servo (FTS) machining. FTS machining uses voice-coil and piezoelectric actuation to produce small-scale features (up to 500 μm) at high frequencies (up to 1 kHz). The machines produce high-density, high-definition patterns in this manner. In contrast, Servoform 3D provides long excursions (multiple millimeters) at low frequencies (<100 Hz). This creates large-scale surface variations. A third method of ultraprecision machining freeform components is the conventional three linear axis *X-Y-Z* machining.

A clear technical advantage

Optical lenses obviously require both accuracy and clarity. The polishing of an irregular or faceted surface such as a Fresnel or prismatic lens becomes a series of compromises. UPM can easily handle this kind of work.

In fact, UPM has lowered the cost of directly machining lenses. It has done the same for manufacturing mold cavities for mass production of lenses. Contact lenses have benefited: Low-cost, disposable con-

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Key points:

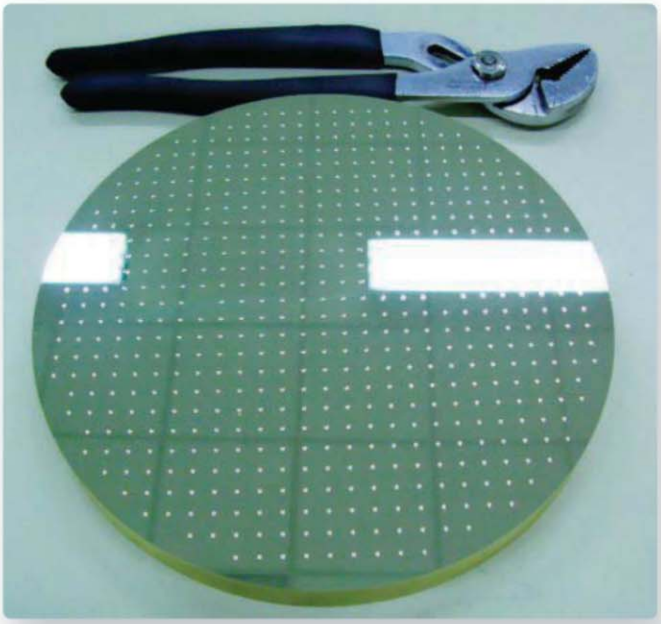
- Ultraprecision machining produces fine finishes not possible with any other machining technology.
- Lower costs has let UPM branch into many industries.
- UPM can also make tiny patterns on parts.

Resources:

Ametek Precitech, *www.precitech.com; www.precitech.com/company-profile/white-papers*

Haydon Kerk Motion Solutions, *www.haydonkerk.com*

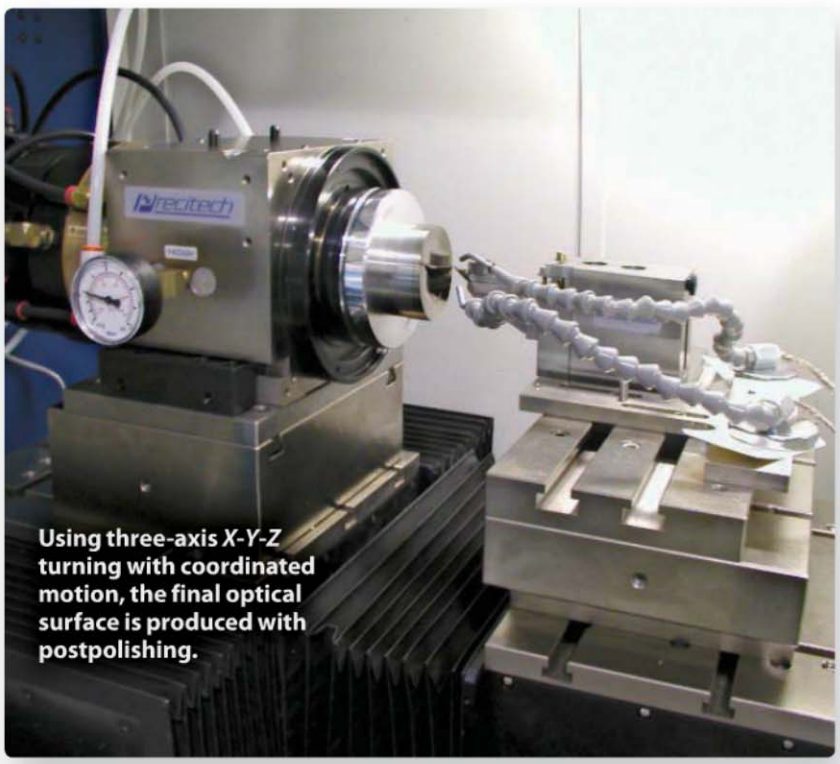
For another feature on finishing technologies, scan this code or go to: *http://machinedesign.com/article/liquid-electrode-finishes-alloy-parts-1026*



Ultra Precision three-axis diamond turning with Precitech's Fast Tool Servo process can produce this 200-mm-diameter brass aspheric-lenslet array mold. Final surface is produced without postpolishing.

tact lenses, and toric lenses for astigmatic vision correction now come in both hard and soft forms at a fraction of the cost of in the past.

In the life sciences, sample sizes have dropped from milliliters to picoliters. Even tolerances of a few microns can have a dramatic effect on picoliter volumes. Open up any typical portable electronic device today — whether a camera, cell phone, insulin pump, or pacemaker — and perform a tolerance analysis on the assembly. The small size of the tolerance budget will be obvious. Everyday systems such as inkjet printers and automotive fuel-injection devices benefit from precision that was impractical 25 years ago. Inkjet cartridges have nozzles in them that are more precise than typical aerospace components, just to make sure every drop of ink is exactly the correct size and lands in the right place.



Using three-axis *X-Y-Z* turning with coordinated motion, the final optical surface is produced with postpolishing.

UPM allows the manufacturing of more-precise measuring equipment and metrology tools than otherwise possible. It can easily support the rule of thumb that measurement tools should be one or two orders of magnitude more accurate than the items they measure.

However, UPM really shines when it comes to creating superior surface finishes for visual impact. Ultraprecision machining can repeatedly generate superior surface finishes and do so with operators who have the same skill set as traditional CNC machinists.

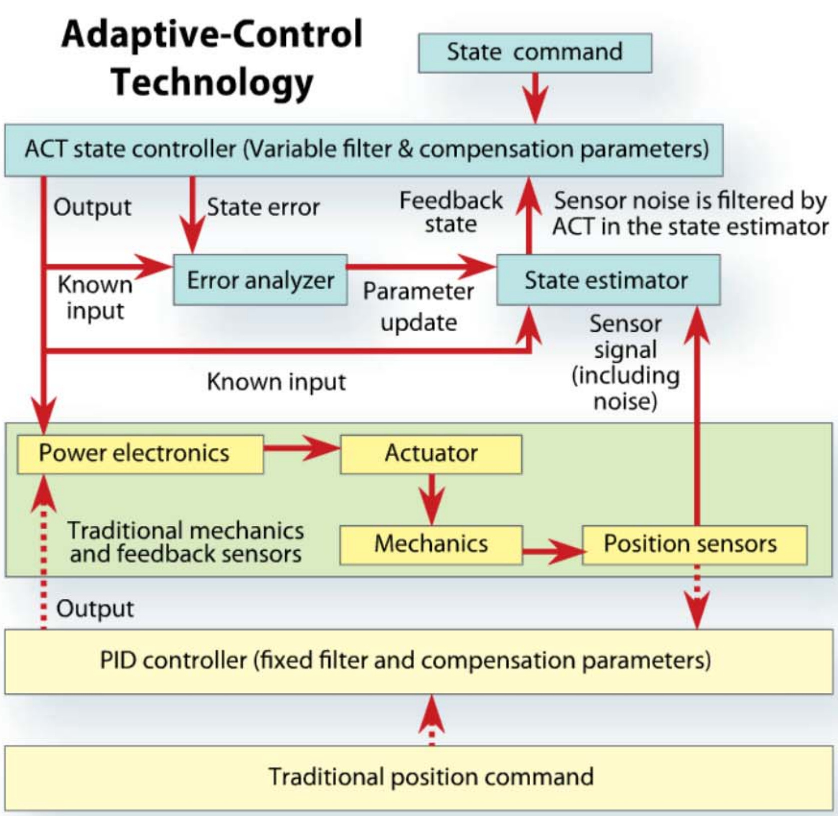
Overall, methods for producing submicron finishes include polishing, lapping, and focused ion-beam milling. However, these are costly, time-consuming processes. UPM offers similar capabilities with fewer steps and process variables. Also, ultraprecision machining is more likely to cut through surface irregularities, preserving the true makeup of the sample. Abrasive techniques tend to drag or smear particulates, which could compromise the quality of the sample's surface.

Special machines

The small diamond tools on UPM machines make only tiny cuts. Therefore, UPM will not replace traditional machining equipment. Instead, it is a complementary process, much like polishing, but with greatly enhanced capabilities. It is not particularly quick, but it is quicker than the alternatives. It is most often used to create tooling or specialized custom parts.

The diamond tools work well on a variety of materials including nonferrous metals such as aluminum, copper, electroless nickel, and tin. They also work well on a variety of polymers. But on ferrous metals, a chemical reaction occurs between the iron and the diamond tool, leading to a breakdown of the diamond surface.

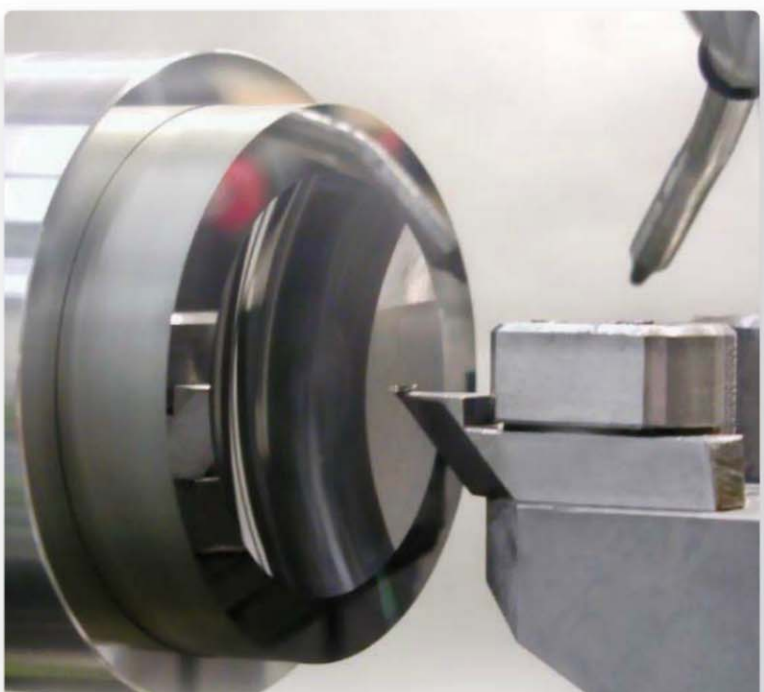
One solution is to lay down an electroless-nickel layer which can be finish-machined with diamond tooling. This combination can obtain a surface finish of 0.4-nm Ra. Another option is to use tooling of cubic-boron nitride (CBN) that is compatible with ferrous materials. Surfaces created with CBN tooling aren't as smooth as those created with diamond on nickel because of the particle size of the



Adaptive-Control Technology (ACT) builds on traditional feedback controls by anticipating repetitive events. The flowchart illustrates the ACT process (green blocks) that adjusts inputs to cancel disturbances that would degrade the accuracy of the UPM machine's movements.

abrasive. But CBN can still produce a finish of 15 to 20-nm Ra or better on electroless nickel. Both of these methods are used for building mold cavities.

Ultraprecision machining can also be used for the deterministic grinding of materials such as glass or ceramics that cannot be turned. Ceramic mold components (typically silicon carbide or tungsten carbide) used for producing glass products can be directly manufactured in this manner. This technology has enabled the low-cost optics found in today's mobile products.



Ultra Precision diamond turning produces an infrared lens of silicon material. Final surface is produced without postpolishing.

Companies building precision injection molds for plastics, especially where surface finish is important, should look into UPM. Mold polishing is an art as much as a science. It is limited in both accuracy and precision compared to ultraprecision machining and is not practical for details containing sharp edges or corners. Electrical-discharge machining, a mainstay for creating complex cavity features, has limitations such as rough surface finish and the risk of surface defects from inadequate flushing that are easily surpassed by ultraprecision machining.

For consumer products, UPM supports the production of high-gloss prototypes in the correct material even if it is translucent or transparent. For technical prototypes, UPM can build proof-of-concept models in metal, glass, and polymeric materials.

It is important to note that UPM is not a fringe or an experimental technology. It is no longer a laboratory process needing a team of scientists to operate. In fact, ultraprecision machining has never been as simple and easy to use as it is today. With production machines shipping worldwide, and prices competitive with other CNC equipment starting in the low six-figure range, the only thing preventing wide-scale adoption is awareness. **MD**