Closing In On Perfection

Ultraprecision machine tools are putting manufacturers within nanometers of absolute accuracy. by Gene Bylinsky

A new chapter is being written in the history of light manipulation. Lenses that return sight to the blind. Smaller ones, the size of a lentil, that make DVD and CD players possible. High-tech lights in cars and homes that can outlast old-fashioned bulbs by decades. What those products have in common is that they, or their enabling components, are made by ultraprecision machine tools. These supermachines stand at the apex of manufacturing, the Rolls-Royces of machine tools. Capable of accuracy on almost an atomic level, they're as close to perfection as manufacturing gets.

For now, about 90% of the products these machines fashion are optical—sophisticated lenses and mirrors that are used in everything from iris scanners and ear thermometers to laser printers and digital cameras. But an increasing number of mechanical components—fuel-injection systems, for example—also require high-precision manufacturing. And the possibilities for new applications are multiplying. Says Herman E. Reedy, executive vice president of II-VI, a $130-million-a-year world leader in laser optics: "Ultraprecision machining allows us to make products today that we could only dream about a few years ago."

That's creating a boom in this small segment of the machine-tool market. The niche, with annual worldwide sales of only about $100 million, is one of the few growing areas in an otherwise shrinking industry. Just two U.S. companies make these machines, and their factories are running at full tilt; European and Japanese firms also compete. The largest U.S. company, Precitech of Keene, N.H., has annual revenues of $20 million and has tripled sales in the past three years. It is on track to sell 75 machines this year. Its sole domestic competitor, Moore Nanotechnology Systems, also of Keene, expects to sell 25 machines this year, pushing revenues to $7 million, from $5 million in 2002.

The machines are expensive at $250,000 to $1 million apiece, or about three to four times the price of similar-sized conventional machine tools, but their accuracy is startling. While in conventional machining—say, drilling holes in bumpers for cars and trucks—an accuracy of 0.001 inch or less is acceptable, ultraprecision machining measures work in nanometers, or a fraction of a millionth of an inch. At its best, precision machining gets down to the atomic level, able to create optical surfaces that would be damaged by the touch of a finger.

To build a machine capable of such precision takes a fair bit of precision itself. It's an exacting process in which each part is isolated by air or oil to prevent friction from mucking things up. To start, a frame made from the highest-quality steel forms the foundation of the machine. The machine housing sits on a 1,000-pound granite slab, which rests on airbags that insulate it from the frame's vibrations. Inside the housing are the guts of the machine: A spindle—a steel shaft—is isolated by a thin layer of air in a brass sleeve. This creates an "air bearing" that stabilizes the spindle as it rotates at up to 15,000 rpm, without the errors that would show up if mechanical bearings were used. The other moving parts of the machine are the slideways. Those, made by Precitech out of a high-quality, fine-grained iron casting known as Durabar, support the spindles, which in turn hold the tool and the work piece.

Like the spindle, the slideways don't come in contact with other metal parts; they float on a thin layer of oil. There's no grinding of the bearings, no brushing of metal against metal—none of the factors that wear out conventional machine tools. Even the flat linear motors used in these machines have no mechanical contact between their coils and other components. It all makes for an extremely smooth operation.

To perform with total precision—and to avoid destroying the

Precitech's diamond-tipped tool removes slivers of copper, creating an industrial mirror.

R&D manager. "We're using a fine control to take a little bit of material off rather than a large amount of power to take off a lot of material." The less power used, the greater the precision of the process.

Diamond turning works well with nonferrous materials such as aluminum, copper, tin, and silver, but it's more complicated to use the process on ferrous metals such as steel or on brittle materials like optical glass. A chemical reaction turns the diamond into graphite, destroying the cutting edge of the tool.

That's a serious limitation, since steel is what's used to make fuel-injection components for car engines, not to mention the molds for millions of CDs, DVDs, contact lenses, and bifocals. To get around this, some users substitute a boron-nitrite tool for the diamond. These aren't as exact as diamonds, but ferrous parts usually do not require the same level of precision as optical components. Other machine users coat the steel with a paper-thin layer of nickel before turning it with a diamond, fooling it into acting like nonferrous material. With these modifications, ferrous metals can be machined to the required accuracy.

The most exciting trend in precision machining is the ability to create optics with so-called free-form geometries. A growing demand for such lenses, mirrors, and other components, which have nonsymmetrical surfaces, has led to the development of machines that can operate on three, four, and even five axes. Inside these machines, the cutting tools and the work pieces engage in an intricate dance. In one advanced technique called raster flycutting—so named because it resembles the raster, or scan, lines of a TV set—the piece being worked on is held stationary while the cutting tool or wheel moves in as many as five axes, like a vastly accelerated sculptor's spatula.

The ability to mass-produce nonsymmetrical, or "aspheric," lenses is leading to astonishing advances in light manipulation. Aspheric lenses concentrate light more efficiently than conventional lenses, sharply reducing the number necessary to make a product work while at the same time increasing its efficacy. That's fueling a boom in all sorts of consumer and industrial electronics. "Ultraprecision machining is doing for light what integrated circuits did for electronics," says Alan R. Hedges, a Ph.D. in optics who manages precision machining at II-VI.

The latest ultraprecision optical systems lie behind the improved accuracy of the laser-guided bombs and missiles used in the war

expensive optical parts they're fashioning—these tools are equipped with computer-controlled devices that continuously sample data from the part as it's being processed and relay that information back to the machine. The working parts of the machine then respond, moving in increments of as little as one nanometer. That movement, known in the industry as resolution, is 250 times more precise than that of conventional machine tools. As a result, surface finishes are now possible that deviate from absolute perfection by only one nanometer—about one-75,000th the thickness of a human hair.

At the heart of an ultraprecision machine is a working tool tipped with a gem-quality diamond. The tiny stone enables "single-point diamond turning," a process used to make a wide variety of electro-optical components—night-vision systems, reflective mirrors for industrial and medical lasers, and telecom components, to name a few.

It works like this: The diamond forms a tool that looks something like the beak of a woodpecker. This tool cleanly "turns," or removes, slivers of metal or plastic from the part rotating in front of it. While conventional tools run on tens of horsepower, "just ounces of thrust are required to keep our machine tool in contact with the material," says Walter Lewandowski, Precitech's

PHOTOGRAPH BY PAXTON

in Iraq, for example. More-mundane applications surround us every day. 3M uses ultraprecision machines to make high-reflectivity tape for highway signs and police cars. Inside the tape, tiny pyramidal lenses make light bounce from one lens to another, and finally back toward the light source. Cameras with zoom lenses that once measured in feet now fit into a jacket pocket. The use of aspherical mirrors in laser printers has cut the length of their scanning system in half and dramatically reduced their cost.

More innovations are coming into use. Consider the growing use of optics in automobiles, such as in the headlights in late-model cars. Not only are they smaller and more elongated than their predecessors, but in the corner you might spot a honeycomb of tiny lenses, put there to better concentrate the light. Other electro-optical devices—light-emitting diodes, or LEDs—are now being used as brake lights in some luxury cars. LEDs are 20 times more efficient than electric bulbs and can last for decades.

Precision optical devices are finding their way into other parts of the car as well. Bishop Steering Technology, a Sydney engineering company, has developed an advanced opto-electronic sensor for power-steering mechanisms. The Bishop torque and angle sensor (BTAS) contains electro-optical chip and sensor modules that would replace the hydraulic and mechanical components in today's steering mechanisms. Bishop sensors on the steering-wheel shaft emit pulses of light that correspond to how far and how hard the driver turns the wheel. The control chip picks up that light and translates it into commands that it then relays electrically to mechanisms that steer the wheels. The system will be manufactured under license by Germany's Robert Bosch, and it is expected to debut in European cars in 2005.

BTAS points the way toward the eventual elimination of mechanical steering, replacing the standard rack-and-pinion system with a computer-age one based on lasers and some 30 precision lenses. It would enable "drive by wire," a concept borrowed from aviation's "fly by wire": Instead of using a steering wheel, drivers could control the car with a side stick like those used in jets. The stick, replete with sensors and electro-optic controls, would transmit the driving data over an electrical wire.

It may sound like the stuff of science fiction, but DaimlerChrysler, GM, and other automakers have already built prototype cars that eliminate steering columns and steering wheels as well as gas and brake pedals. Partial drive-by-wire has been showing up in recent models, including the elimination of the throttle cable in Ford's '03 Lincoln LS and its Thunderbird. Earlier this year DaimlerChrysler bought a 30% stake in Bishop Technologies, the parent of Bishop Steering, and also 100% of Bishop Steering's German subsidiary.

Wide adoption of drive-by-wire systems would be a huge boon to precision-tool makers. "I can count the number of lenses in the car on the fingers of one hand. Most of them are in the CD player," says Precitech CEO David Davis. "Now all of a sudden the steering mechanism will contain 30 lenses."

Perhaps the most important use of precision machining is in helping functionally blind people regain sight. Some 50,000 Americans and hundreds of thousands more around the world suffer from serious damage to the cornea, the clear dome that covers the front of the eye and helps it focus. If the cornea is damaged, light can cause unbearable pain, so most of those afflicted are forced to spend their lives in darkened rooms, seeing virtually nothing.

Perry Rosenthal, a diminutive dynamo of an ophthalmologist, is using precision machining to change that. Rosenthal, who heads the nonprofit Boston Foundation for Sight, has resurrected and refined a 100-year-old German invention that fits over the sclera, or white of the eye. Unlike normal contact lenses, these arch over the cornea without touching it, enabling those with damaged corneas to wear them. Using such lenses, Rosenthal began treating patients with some success. His lens production didn't really pick up, however, until two years ago, when his clinic acquired a $275,000 machine from Precitech, financed by a grant from Bausch & Lomb.

The new machine has both accelerated Rosenthal's output and improved the lenses. To avoid sticking to the eye and injuring it, the lenses need tiny grooves on their inner surface; these serve as conduits for tears, the eye's natural lubricant. Before, when the lenses were made on a far less reliable lathe, the channels had to be laboriously dug by hand; now they are inscribed automatically.

The 400 people who now wear the Boston scleral lens include a young woman who could then resume her career as an artist, a grandmother who saw her grandchildren for the first time, and a young FedEx employee in Philadelphia who was able to return to work, saying that he now believed "in miracles." That may seem like divine intervention, but it's really just an example of what's possible with extreme precision. ■

Let there be light

The Boston Foundation for Sight uses an ultraprecision machine tool to make scleral lenses, which fit over the white of the eye and can restore sight to those suffering from severe corneal damage.

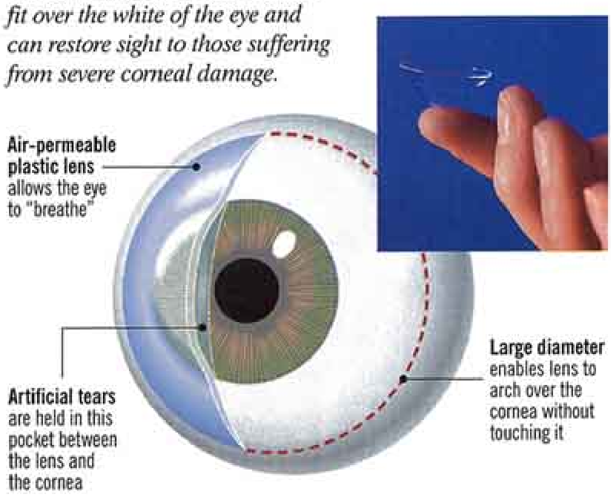

DIAGRAM BY GUILBERT GATES

FEEDBACK fortunemail_letters@fortunemail.com. Stories from the Industrial Management & Technology section can be found at fortune.com/imt. Executives in manufacturing and research and others eligible to receive FORTUNE's Industrial Edition can subscribe by calling 888-394-5472.