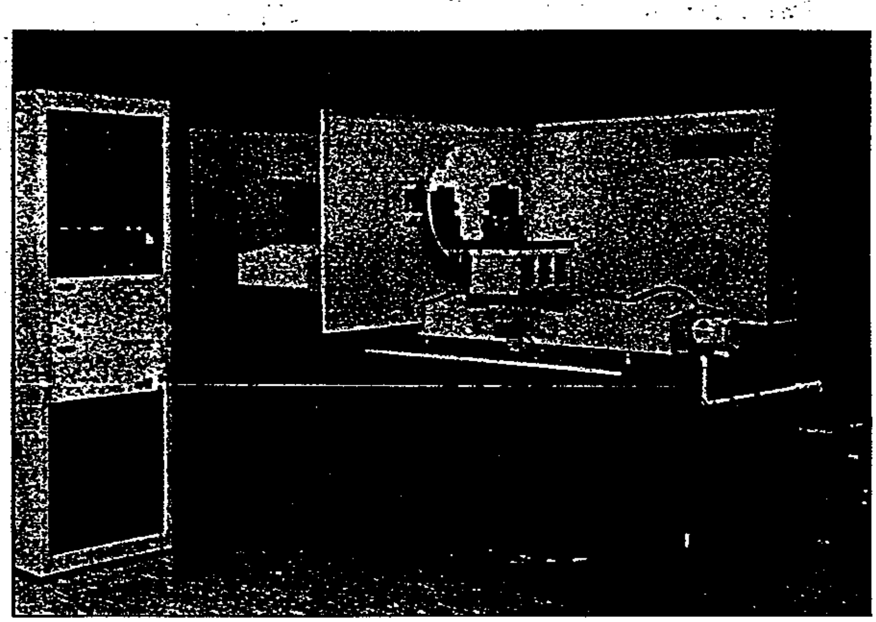
Diamond turning achieves nanometer smoothness

Direct diamond turning of visible-wavelength optical surfaces could change future fabrication procedures.

By David H. Youden



RANK TAYLOR HOBSON INC.

Single-point diamond-turning machine produces fine surface finishes on parts for optical systems that use light at wavelengths as short as 500 nm.

Single-point diamond turning machines are among the most precise lathes ever devised. These machines are designed to produce fine surface finishes on aspheric mirrors, IR optics, lens molds, high-energy laser mirrors, and other parts that require specularly reflecting surfaces accurate to a few tens of nanometers. To successfully design machines of this accuracy, a great deal of attention must be paid to seemingly minor details.

Sources of error must be considered

A successful diamond turning machine is one in which all sources of vibration have been eliminated, isolated, or controlled. Every source of heat on or near the machine must be evaluated, and the effect upon the thermal stability of the machining environment must be determined. All potential errors in geometry must be considered and, if possible, eliminated. Where geometric errors cannot be eliminated they must be mapped and compensation schemes applied.

Sources of acoustic noise must be considered. No disturbing influence is too small to ignore. There have been cases in which music from a nearby radio has adversely affected the surfaces produced by these sensitive machines.

The workpiece machined on a diamond turning machine is often made of aluminum, although copper is also common. Other diamond-turnable materials include silicon, germanium, brass, gold, silver, acrylic, zinc selenide, electroless nickel plate, and other nonferrous materials.

Rank Pneumo, a division of my company, has recently introduced the Nanoform 600 into its range of single-point diamond turning and grinding machines. This newly designed diamond turning machine has the capability of producing spherical, flat, and aspheric surfaces that are directly usable in optical systems that use visible light, that is, at wavelengths as short as 500 nm. This new machine has been under development for three years, during which time a number of unusual design features have been perfected. These features contribute to its ability to make highly precise parts.

New machine developed

This machine, like its predecessors, is a two-axis, tee-base lathe. The tee-base designation refers to the arrangement of the slides, which, when viewed from above, form the letter T, with the x-axis slide as the crossbar of the T extending to either side of the z-axis slide.

The machine is constructed of mod-

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ular components, which can be assembled in a variety of ways for specific tasks. The major modules are the two identical slides and the spindle. Other modules include vibration-isolation and leveling equipment, a vacuum system, a coolant system, and a hydraulic system. The two slides have rigid, nontelescoping covers over their ways. They are mounted on the machine so that the moving covers over the z-axis ways pass beneath the x-axis slide. This vertical staggering of the slides allows the machine to turn a large diameter workpiece without requiring the spindle to be raised high above the slide that carries it.

The spindle is mounted on the x-axis slide so that its axis of rotation is perpendicular to the motion of that slide and parallel to the motion of the z-axis slide.

The z-axis slide carries the cutting tool. The tool most often used is a single-crystal natural diamond of gem quality, which has been carefully shaped and mounted in a steel shank. The quality of the edge of the diamond tool is one of the critical factors that allow very fine surface finishes to be obtained on the machine.

The base is a casting made of synthetic granite, a mixture of granite chips of various sizes, and an epoxy binder. The granite makes up about 95% of the material by volume, and, thus, the finished casting has mechanical properties very similar to those of natural granite. Using a castable material allows much of the machine structure to be molded into the casting, thereby eliminating the need for separate risers and allowing drainage

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channels for coolant. Threaded inserts are cast into the base where components are to be attached to the synthetic granite. In some critical areas, steel plates are grouted to the base to form mounting surfaces for the slides and metrology equipment.

Beneath the base is a pneumatic vibration-isolation system that prevents vibrations in the floor from reaching the cutting tool. The vibration-isolation system incorporates a self-leveling feature that maintains the base in a level attitude despite movement of the slides.

New slide design

The slides themselves are one of the keys to the machine's performance. They move on frictionless, oil hydrostatic bearings. Figure 1 illustrates the construction of the slides, showing the hydrostatic bearings and other features of the slide design. These bearings function by forming a thin, pressurized film of oil between the moving slide and the stationary ways. This machine and the smaller Rank Pneumo ASG 2500 are the only U.S.-built diamond turning machines with oil hydrostatic ways.

Previously, hydrostatic ways were in use only on diamond turning machines installed at Lawrence Livermore National Laboratory (Livermore, CA) and at a few corporate development labs. Other commercially available machines have either roller way systems or air-bearing ways—designs that are less rigid and have far less damping. Oil bearings are used because these bearings provide high stiffness and high damping while averaging any defects that may be present in the geometry of the slide ways.

The slides on the prototype machine are moved by ball screws with preloaded nuts. Because even the highest-quality ball screws generate small disturbing forces caused by geometric errors, the slides of this machine are isolated from these forces by intermediate slides that run on ball bearings and are located beneath the main slides. The ball nuts are attached to these intermediate slides, which, in turn, drive the main slides through hydrostatic thrust bearings located between the ways. In this manner, the main slides are isolated from all contact with the machine and all disturbing forces caused by the drive mechanisms. The slides are specified to travel straight to within 0.2 μm (8 μin) in their 300-mm (12-in) stroke.

Rigid way covers are used to protect the ways from chips and coolant. These covers do not generate vibrations when the slides move, nor do they impose forces on the slide, as do telescoping or collapsing bellows-type covers. No other diamond-turning-

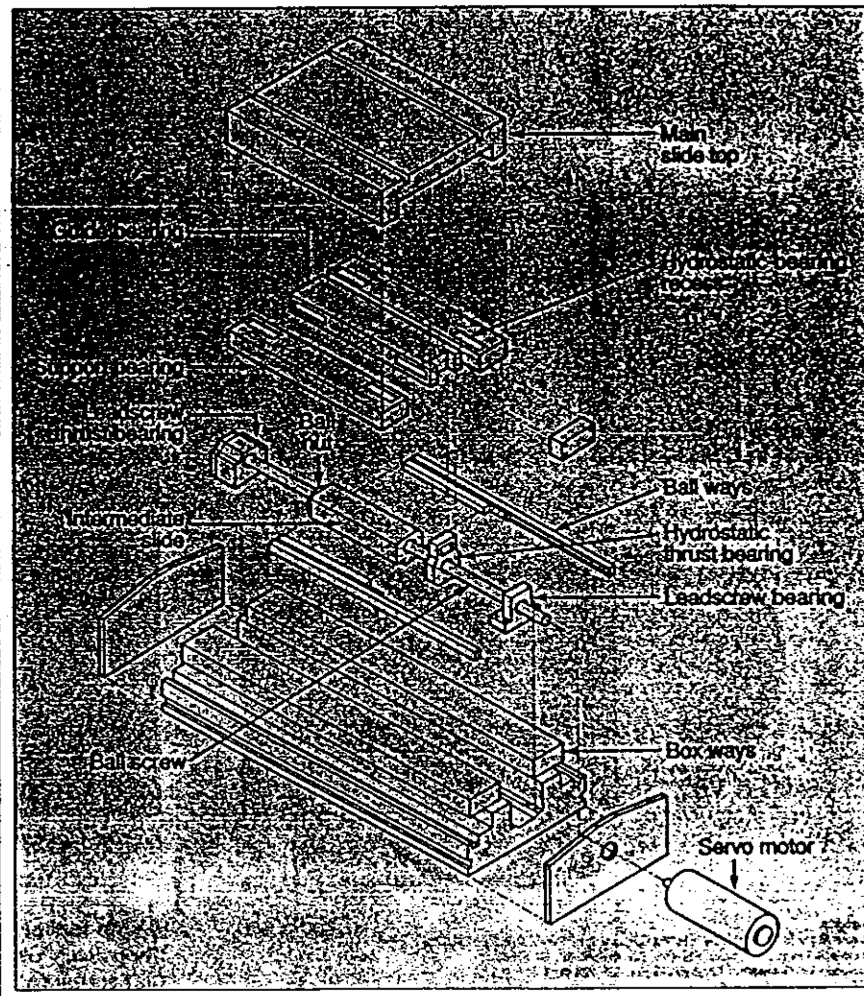

FIGURE 1: Hydrostatic bearings are used in this Rank Pneumo single-point diamond turning and grinding machine. The intermediate slide with its ball nut and hydrostatic thrust bearing fits between the box ways.

machine design addresses this as a source of errors.

This is also the only machine that compensates both for variations in the refractive index of air and for thermally induced changes in machine structure. Other vendors rely upon the machine operation to make appropriate in-process corrections.

Special spindle design

The specially designed spindle carries the workpiece. It uses air bearings to achieve smooth, frictionless rotation. The thrust bearing on the spindle is located toward the front of the spindle housing to better control any axial movement of the work caused by heating of the spindle when it rotates. Although the amount of heat generated by the spindle is small, control of the axial position of the part is crucial and demands that attention be paid to all potential sources of errors. The spindle housing is unusual because it attaches to the slide by means of ears located at the same height as the spindle center line. This method of mounting prevents the spindle center line from moving vertically when the spindle warms due to heat generated when it rotates.

The spindle is driven by a water-cooled ac motor mounted directly behind the rear journal bearing, which can rotate the spindle at any speed from 360 through 3600 rpm. Parts may be fixed to the work spindle by a variety of methods, but the most common is the use of a vacuum chuck.

On the operator's side of the work spindle there is a tool-setting station.

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The tool setter consists of a pair of air bearing linear variable differential transformers (LVDTs), which are used to measure the height of the tool relative to the center line of the spindle and the exact position of the tool relative to the spindle center line along the x-axis. Many of the parts cut on machines of this type require that the tool end its cutting exactly at the center of the part. Because of this, the tool position relative to the spindle center line must be known to within a few nanometers.

The machine's computerized numerical control (CNC) system requires the position of the machine slides be known at all times. This position information is gathered by two laser distance-measuring interferometers, one on each axis. The interferometers are differential plane-mirror devices that have a resolution of 1.25 nm (0.05 μin). In addition, there is a third interferometer that measures a fixed distance and compares measurements made through a vacuum with those made through air to determine the refractive index of the air in the beam path. Information from this interferometer is combined with that obtained from the other two to arrive at the positions of the machine slides.

Different approach to metrology

To achieve the highest level of accuracy, some machines are designed so that all metrology is done with reference to a kinematically mounted, unstressed structure called a metrology frame. This machine takes a different approach to the problem of metrology. Figure 2 shows the general layout of the laser interferometry used for position feedback. One physical point on the machine structure has been designated as the point from which all displacements are measured. This point lies on an imaginary vertical line that passes through the tip of the tool when the tool is just touching the face of the chuck at the spindle center line.

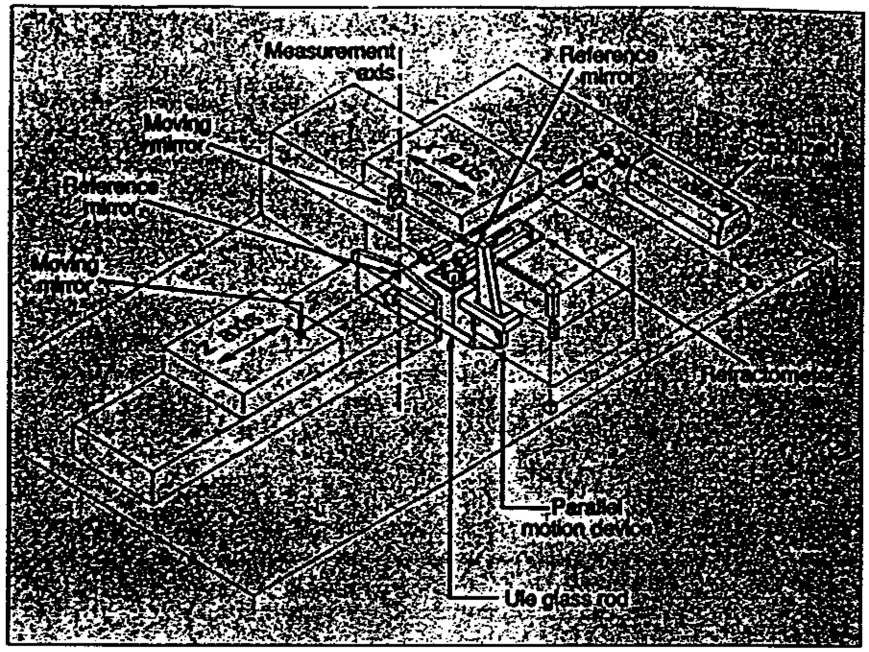

FIGURE 2: Ultralow-expansion glass rod and parallel-motion device combine with the refractometer in this laser metrology system to stabilize the machine in a changing thermal environment. The measurement axis passes through the tip of the cutting tool and the center of the chuck when the two are in contact.

The stationary reference mirror of the z-axis interferometer is located on the z-axis base, at a point on the imaginary line just beneath the z-axis way covers. The z-axis moving mirror, which is almost in contact with the stationary mirror when the tool is touching the chuck, is mounted on the front face of the z-axis slide.

The x-axis metrology is somewhat more complex, because the workpiece interferes with the mirror placement. To solve this problem, we have kinematically mounted a 300-mm-long (12-in) bar of ultralow-expansion glass so that one end of the bar is fixed to the z-axis base adjacent to the z-axis fixed mirror and on the vertical line previously described. The other end of the glass is held in the lower end of a parallel-motion mechanism so that it is in line, vertically, with the x-axis stationary mirror, which is mounted on the upper end of the mechanism just below the top of the x-axis slide. The x-axis moving mirror is located on the slide directly below the spindle center line and just behind the face of the chuck.

This unique metrology arrangement, for which a patent has been sought, is smaller, less costly, and potentially more accurate than a conventional metrology frame. Figure 3 compares this x-axis metrology and a similar, uncompensated system.

Computer control of the lathe

The CNC that operates the lathe uses distributed processing to provide fast response and good number-crunching capability. An 80286 processor controls the screen and operator interface, while a series of 80186 processors is dedicated to closing the servo loops and running various other I/O functions, such as monitoring the pressure switches and limit switches in use throughout the machine.

The controller, along with the laser-interferometer electronics and the servo amplifiers, is mounted in a separate, free-standing cabinet, so that the mechanical noise generated by the fans contained in these units cannot be transmitted to the machine itself. Other free-standing auxiliary equipment includes the vacuum pump, the hydraulic pump that supplies oil to the slide ways, and the air dryer for the spindle.

The rewards for the effort expended on the design have been significant in terms of the surface finish and form

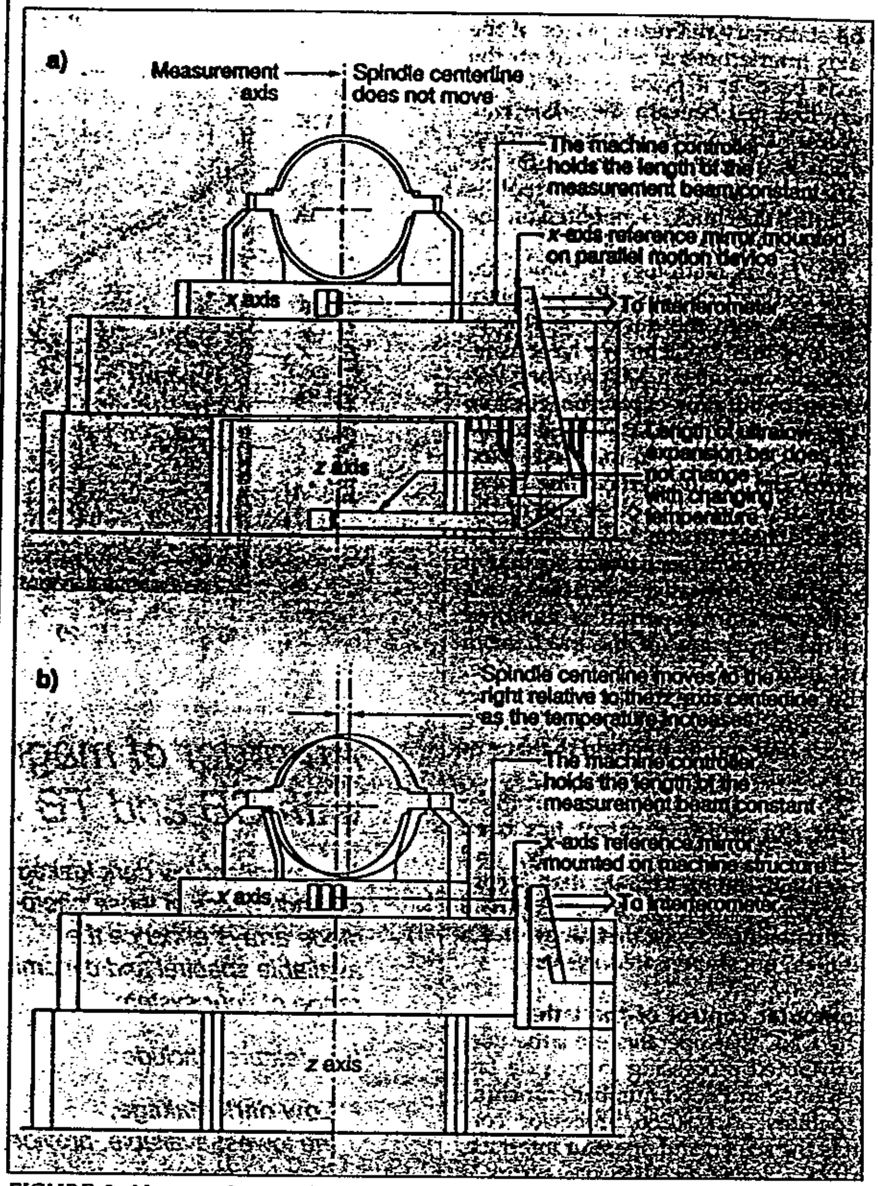

FIGURE 3: New x-axis metrology system (a) operates to eliminate movement of the spindle center line relative to the tool, which is mounted on the center line of the z-axis. A conventional metrology system (b) allows the spindle center line to drift about as the temperature of the machine varies. Temperature changes are usually less than 0.5°C.

accuracies that can be achieved on various workpieces. Contoured surfaces have been generated in OFHC copper with a surface smoothness of less than 10 nm peak-to-valley as measured on a Talystep surface profilometer. These surfaces can be made true to form within one-sixth wave at 632.8 nm (approximately 4 μin). A 450-mm-diameter aluminum plano mirror has been generated flat to within less than one-half wave (approximately 12 μin). Finally, a flat, electroless-nickel-plated witness sample has been diamond turned to a surface finish of less than 5-nm peak-to-valley. We consider these results significant accomplishments in the field of single-point diamond machining of optical surfaces and expect them to influence future manufacturing techniques. □

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