DESCRIPTION OF A UNIQUE MACHINE TOOL
PERMITTING ACHIEVEMENT OF <15-A rms
DIAMOND-TURNED SURFACES*

D. M. Miller, G. H. Hauver,
J. N. Culverhouse, E. N. Greenwell
Pacific Northwest Laboratory
Richland, Washington 99352

MASTER

Abstract

A new machine tool now in the final stages of development at the Pacific Northwest Laboratory uses a unique tool motion to produce diamond-turned surfaces of exceptionally high quality. The cutting tool is programmed to move in 4-nm increments along two axes: an X axis and an Omega axis. Exceptionally stiff and accurate control of the tool is possible with this "Omega-X" system. Copper surfaces of revolution have been produced with a 12.3-A rms surface finish and a contour accuracy of 75 nm. In conjunction with a unique, thermally stabilized air bearing spindle and machine calibration equipment, the Omega-X system permits a significant advance in the fabrication of optical-quality surfaces for use with the visible spectrum.

Introduction

For more than four years, the Pacific Northwest Laboratory has been developing the Omega-X nanometer machine tool,** illustrated in Figure 1, for the production of ultra-smooth, accurately contoured, diamond-point-machined surfaces. Although the machine tool is still under development, goals of a 15-A rms surface finish and a 100-nm contour accuracy have been demonstrated on 5-cm-diameter OFHC disks. A disk surface finish of 12.3 A rms (as determined by total integrated scatter measurements) and a contour accuracy of 75 nm were measured at the Naval Weapons Center, China Lake, California. These measurements were made at the request of the NASA-Goddard Space Flight Center, Greenbelt, Maryland.† Kitt Peak National Observatory in Tucson, Arizona evaluated a machined, 5-cm-diameter aluminum disk and found the disk very adequate for Next Generation Telescope mirrors from the standpoint of reflectivity and light scatter.

The machine tool incorporates several unique features to attain these high-quality surfaces, including the Omega-X contouring system, fully programmed computer operation with feedback and error correction, and a thermally stabilized air bearing spindle driven by a torque-balanced, vibrationless coupling through a torque-smoothing pulley. Special equipment and procedures were developed for machine alignment, calibration, and tool setting. The equipment and procedures described here are considered to permit a significant advance in the fabrication of optical-quality diamond-turned surfaces for use with the visible light spectrum.

Major Machine Components and Systems

Omega-X Contouring System

The principal feature that permits the achievements described for this unique machine tool is the Omega-X tool motion shown in Figure 2. This motion is partly accomplished by attaching the back end of the cutting tool bar to an eccentrically rotating bearing. The bearing rotates along the Omega axis, providing the cutting tool's Omega component of motion. The location of the Omega axis is rigidly positioned by the machine tool's Z-axis slide, which is motionless during the cutting process. The front end of the tool bar with the cutting tool passes through a pivoting, linear, hydrostatic oil bearing that is attached to the X-axis slide. The slide is servo driven, providing motion along the X-axis.

- *The research work leading to this paper was performed for the U.S. Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA), and later the Department of Energy (DOE) under contracts E (45-1):1830 and EY-76-C-06-1830.
- **Miller, D. M., April 11, 1978. "Omega-X Micromachining System." U.S. Patent #4,083,272, U.S. Patent Office, Washington D.C.
- †Contract No. NAS 5-23874 "Establish Sputter Deposition and Single Point Diamond Turning Parameters for Generation of Glancing Incidence Paraboloid Mirror for NASA Evaluation." March 22, 1977 to February 25, 1978.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FIGURE 1. Omega-X Nanometer Machine Tool

FIGURE 2. Omega-X Tool Motion

In conventional fine-machining tools a tool bar is mounted on two moving slides to provide tool bar motion. These slides may weigh from several hundred kilograms to several metric tons in order to provide tool bar stiffness and control. On the Omega-X machine the tool bar is also the slide and weighs only 36 kg. The tool bar is mounted in the pivoting hydrostatic oil bearing rather than being rigidly attached to a moving slide, as is the case with conventional machines. The tool bar is free to slide along its axis through this linear bearing; thus the detrimental motion errors of the X slide cannot be transmitted to the cutting tool. The increased stiffness and precise control required for tool bar motion is achieved by the Omega-axis eccentric mechanism. Hydrostatic bearings are used for the rotating eccentric and the pivot to provide maximum stiffness and to avoid ball bearing mechanical noise. Backlash is eliminated by constant-force springs applied in opposition to the feed motions on both the X and Omega axes.

The ultrasmooth, accurately contoured surface on the workpiece is created by computer coordination of tool-bar travel along the rotating Omega (in-and-out) and the linear X (side-to-side) axes. If the Omega axis is held stationary, the X-axis motion swings the tool bar through an arc, producing a concave surface. For contours other than this natural concave, the Omega eccentric must be used. Precisely controlled tool motion with increments no greater than 4 nm is achieved by the angular rotation of the eccentric. The amount of eccentric offset is adjustable and can be changed to provide an offset of the Omega axis suitable for cutting a required contour. Contours of various figures of revolution can be machined as shown in Figures 3, 4, 5, and 6, which illustrate the motions of the Omega axis and X slide. The machine has a diameter capacity of 1 m and a contouring figure depth of 20 cm, either concave or convex.

FIGURE 3. Omega-X Concave Hemisphere Contouring

The Omega-X system has several advantages over other contouring methods:

- The tool bar is very stiff and supports the cutting tool in the best possible way because the bar is so massive relative to the tool itself. Yet because the tool bar weighs only 36 kg, it is very easily controlled by the stiff, rigid Omega axis.
- The Omega axis mechanism offers stiffer control of the tool bar and cutting tool than a conventional lead screw mechanism operating with much heavier loads. Since the tool bar is also the tool slide, its light weight minimizes inertia by reducing the mass actually moved toward the workpiece.
- Control of the tool's contouring motions occurs approximately at the work spindle centerline height, virtually eliminating Abbe' offset errors.
- Tool motion increments during a contouring operation never exceed 4 nm.
- The pivoting linear bearing is a "captured" type: the tool bar is completely surrounded by the bearing with more than 318 kg of force applied to each of the bar's four sides. Thus the tool bar is very rigidly supported against cutting forces yet

slides through the bearing with no resistance to movement as it is guided by the Omega axis. Also, the 23-cm-long bearing provides an averaging effect for the straightness of the tool bar path because the surface of the tool bar has a slight waviness of short (5- to 8-cm) periodicity.

- X-axis slide motion errors such as yaw and roll cannot be transmitted to the tool because the tool bar is free to slide within the pivoting linear bearing.
- The effect of setup errors, such as tool bar length, tool tip horizontal offset, and spindle centerline offset, have little effect on the contour accuracy of flats or lens shapes with large radii of curvature. For instance, if the tool bar were 254 nm longer than its present 1-m length, the additional length would make no difference in the flatness of a 50-cm-diameter plate and would make a 100-cm-diameter plane surface concave by only 25.4 nm.
- Unlike more conventional machining systems, the Omega-X machine tool has no useful motions without computer control, except for the natural concave produced when the Omega axis is stationary. Use of the computer allows precise control of lathe motion and error correction for repeatable machine errors recorded during calibrations.

FIGURE 4. Omega-X Convex Hemisphere Contouring

Machine Tool Base

The Omega-X mechanism is attached to the X and Z slides of a large (8-metric-ton) machine tool base as shown in Figure 1. The machine base is from a used Heald stacked-slides, dual-spindle, turning and boring machine. It had been in use in production for over 10 years, but was in excellent condition. Measurements of its slideways for straightness and parallelism revealed no error greater than $7.6 \mu\text{m}$. Reworking of the slideways by diamond lapping with charged laps reduced this error to no more than $0.76 \mu\text{m}$ at any point. Top slideway surfaces were measured for straightness with a dual-head electronic level used in the differential measuring mode, which cancelled the effect of the shifting weight of the level head. Straightness of side surfaces of the slideways was measured with a laser interferometer using an angle-determining fixture.

Garlock Multifil 426[®] antifriction material was applied to the wear surfaces of both the X and Z slides. This significantly reduced the torque required to drive the X slide, but did not affect the motion of the Z slide.

The machine came equipped with large preloaded ball screws to drive both the X and Z axes. These ball screws were necessary to drive and control the large slide masses. The X-slide ball screw was replaced with a ground and lapped conventional lead screw to eliminate a detrimental random error detected in the ball screw.

The machine tool base was placed on air mounts to isolate it from vibrations. Because of the geometry of the machine base, four air mounts were used as shown in Figure 1 instead of the conventional three. Three fluidic level controls are used to regulate the air mounts; two of the air mounts are interconnected with a large-diameter tube with the

FIGURE 5. Omega-X Parabola Contouring

FIGURE 6. Omega-X Axicon Contouring

control piping causing them to act as a single air bag. Air mount pressures are set as low as possible with the metering valves adjusted for a slower-than-usual reaction time. Higher air pressures and faster valve reaction times contributed to machine motions that caused surface finish problems.

Servo Drives and Information Encoders

Motion along the X and Omega axes is applied by dc servo motors. On the X axis the gear ratio between the motor and the 0.2-in.-pitch lead screw is 640:1 or 126 revolutions per millimeter of X-axis motion. A primary shaft angle encoder attached directly to the lead screw makes 2×10^{18} divisions of each revolution and provides closed-loop feedback and position information for programmed control. A 5192-bit secondary encoder controls X-axis feed motion increments, dividing each millimeter into 6.5×10^7 parts or 1.529 nm/bit.

The rotation of the Omega axis itself is driven by a Moore high-precision rotary table. The gear ratio used here is 1800:1, and a 5192-bit secondary shaft encoder provides 9.3456×10^7 divisions of the Omega axis revolution. A 5192-bit primary shaft angle encoder attached directly to the Moore table worm shaft provides the closed-loop computer control information.

Spindle Design and Fabrication

The single most important element of a turning machine is the spindle, and machine accuracy can be no better than that built into the spindle. Several design features of the Omega-X machine spindle (Figure 7) differ from those of a conventional opposed-hemispherical journal-type air bearing spindle:

- The permeable graphite bearings are not segmented. This is an advantage because there are no gaps in the supporting air film at segment joints into which the protruding lobes on the spherical journal can drop. It also makes the spindle more economical to fabricate.
- The angle of bearing contact was increased from the conventional 80 degrees to 115 degrees. This provides greater stiffness both axially and radially with added load-carrying capacity. Thus, the spindle is less likely to respond to natural-frequency machine motions.
- Internal oil cooling was incorporated to provide thermal stabilization by drawing away the heat generated in the front spherical zone.

FIGURE 7. Air Bearing Spindle

- Incorporation of on-machine balancing of the mounted workpiece eliminates the effect of the offset of its geometrical center due to imbalance.
- The spindle nose is fitted to accommodate bolt-on fixturing and D-1, 6-in.-type adaptations. Also, a rotary coupling permits either vacuum or pressure to be applied to the work holders.

Special techniques were developed to lap the spindle component parts to their final desired accuracy. Some of these employed the cleaning away of swarf accumulations with detergent and controlled-temperature water. The first step in achieving the final accuracy of this spindle was the development of optically flat, $\lambda/4$ cast iron reference surfaces, which were used as marking tools in producing flat laps and other flat surfaces.

Spindle Drive Coupling

The torque-balanced, vibrationless rotary coupling is a simple, economical device that overcomes all the problems associated with spindle rotation on high-accuracy machine tools. Its only drawback is that it cannot tolerate rapid speed fluctuations. The coupling transmits only balanced torsional forces and cannot exert any axial or radial forces on the spindle. Its reliability has been proven with two years of use during development of the Omega-X prototype. The coupling will also tolerate gross momentary misalignment caused by loading changes on an airbag-supported machine.

Calibration and Standardization

Calibration of Tool Bar Movement

Calibration of tool bar movement in the Omega-X system is accomplished by comparing laser interferometer measurement data with the computer program directing tool bar movement. For X-axis calibration, the interferometer determines X-axis slide position information for the center of the pivot bearing at spindle centerline height. Measurements at 25-nm increments are made possible by the high-resolution shaft angle encoder attached directly to the slide's lead screw. The exact position information is then stored in the memory of the microcomputer that operates the machine tool for later use in error correction to match the exact machine position with the machining program.

For calibration of the Omega axis movement, a laser head is mounted by special fixturing to the pivoting linear bearing, which keeps the laser head aligned with the tool bar. Then by the use of two beam benders, as shown in Figure 8, the actual Omega axis movement of the tool bar is determined directly at spindle centerline height for comparison with the machining program. By running the Omega axis through 180° of rotation, twice the eccentric offset can be measured as a self-proving technique.

FIGURE 8. Eccentric Offset Calibrator for Omega Axis Motion

The length standard shown in Figure 9 establishes the exact center-to-center distance between the pivot bearing and the Omega axis. In this view, the anvil end of the length standard is rested against the pivot bearing alignment ball while the exact center-to-center distance is determined using the linear variable differential transformer (LVDT) contained in the differential screw micrometer as shown in Figure 10. The LVDT is adjusted to a zero reading at its null position against a gage block wrung to the end of the length standard. Then the precise difference between the length standard and the center-to-center distance can be obtained.

FIGURE 9. Spindle-to-Spindle Center Distance Calibrating Device

FIGURE 10. Length Difference Comparator

The exact length of the tool bar is established by positioning the tool bar length standard through the tool bar as shown in Figure 11. The standard's large end, containing the differential micrometer-adjusted LVDT, is referenced against the eccentric master ball. The standard's small end, extending through the tool bar head, indicates where the cutting tool tip should be when it replaces the length standard. The calibration fixture mastering station shown in Figure 12 is then used in conjunction with the tool calibration fixture shown in Figure 13 to establish a permanent reference for tool bar length. To do this, the anvil of the mastering station is adjusted by grinding and lapping a shim until its measurement using the calibration fixture exactly coincides with that of the length standard extending from the tool bar head. The length standard is then removed and the cutting tool inserted into the tool bar head. The tool is adjusted until the tool bar length as measured by the calibration fixture matches the reference supplied by the mastering station.

The tool calibration fixture in Figure 13 also provides a convenient means of measuring tool offset and tool height once the required height setting is known.

Total System Alignment

Total system alignment as shown in Figure 1 requires the spindle centerline to coincide exactly with the Z axis and the Omega-axis vertical centerline. A "home" (zero) position is then established by positioning the pivot bearing center and the tool tip on this centerline with the tool bar exactly aligned to the centerline.

Tool Centering

After tool bar length and tool tip height are established, the tool tip must be centered. The tool centering fixture shown in Figure 9 uses a V-notched cartridge for tool tip centering. The V notch, which is made precisely symmetrically with the diameter of the cartridge, is brought into contact with the tool nose radius slightly below the tool's cutting edge. Then by indicating around the diameter of the cartridge from the spindle, the tool can be adjusted sideways until centering is achieved. This must be done with all machine axes at zero position. With zero tool position established in this manner, a permanent reference is established using the LVDT as shown in Figure 14 to avoid the time-consuming use of sweep indicating techniques.

FIGURE 11. Tool Bar Length Standard

FIGURE 12. Calibration Fixture Mastering Station

FIGURE 13. Tool Calibration Fixture Showing the Tool Setting Operation for Bar Length and Tool Height

FIGURE 14. Air Bearing Tool Centering Fixture

Self-Proving Techniques in Alignment and Calibration

The use of self-proving techniques throughout the alignment and calibration of the machine has provided full confidence in the system. Techniques include such time-proven methods as the reversal of a spindle-mounted straightedge to establish slideway straightness and spindle perpendicularity, the proving of test ball roundness by the Donaldson method, and the use of both cylindrical and flat test cuts to eliminate doubt of alignment accuracy. Since the Omega-X mechanism does not normally produce plane surfaces, the machining and optical evaluation of a flat is a good method of testing system accuracy.

Thermal Stabilization

To avoid thermal drift and instability due to temperature gradients, the entire machine is showered with temperature-controlled oil during operation.

Computer Programming and Control

The programming for the Omega-X lathe has two major portions:

- 1) calculation of the machine motions required to produce the chosen contour
- 2) control of the lathe to duplicate the calculated motions.

The motion calculation program is coded in FORTRAN and is presently run on a Systems Engineering Laboratories (SEL) 810B computer, though any machine with FORTRAN could be used. Working from the dimensions of the particular Omega-X setup chosen and the equation of the desired part contour, the FORTRAN program produces position, velocity, and acceleration data for both axes at a number of points along the contour. An error correction subroutine compensates for repeatable machine errors, using calibrations obtained previously by laser interferometer position measurements. These data can be saved for later use or immediately sent to the machine.

The Omega-X machine is controlled by a dedicated microcomputer programmed in assembly language. Motion data generated by the FORTRAN program on the larger computer are loaded into the computer before cutting a new contour. By commanding the axes control motors the computer makes the position encoder outputs duplicate the motion data previously stored in memory, using smooth interpolations between the data points. The computer program also includes operator commands for moving to any desired position, position readout, or origin relocation.

Improvements Resulting from Operating Experience

The machining of test specimens revealed many imperfections. It was found that the dc spindle drive motor would gradually drift down in speed by 0.2%; when the feedback system commanded more speed the speed change would jerk the machine. This problem was eliminated by using a synchronous motor with a variable frequency drive for speed adjustment.

Machine frame motions resulting from natural frequency undulations were found to cause surface finish problems. Regulation of the pressure in the air mount suspension system and restriction of air mount reaction time corrected the problem.

Solution of the preceding problems unmasked still another contributor to unacceptable surface variations: ball bearing mechanical noise in the Omega axis was causing very slight surface unevenness something like an orange peel effect. All the ball bearings in the Omega axis and the pivot bearing were replaced with hydrostatic oil bearings.

The machine tool came equipped with preloaded ball screws for driving the X-axis and Z-axis slides. The X-axis ball screw was found to contribute random error problems when surfaces nearing parallel to the Z-axis were being cut. Laser interferometer tests were conducted, measuring the X-axis slide position in 1/4-lightwave increments while the slide was commanded to move at a steady rate. Random position errors of 150 to 225 nm were detected and eventually attributed to deleterious action within the preloaded ball screw nut. Included in these tests were measurements of the ball screw end translation while in motion and backlash or looseness within the ball nut. Neither was contributing to the surface roughness problem. A new ground and lapped lead screw was installed to replace the ball screw.

As an additional improvement the original X and Omega servo motors were replaced with more finely controllable units having twice the rotational speed, which eliminated the need for slewing motors.

Recent Test Results

Kitt Peak Observatory evaluated three aluminum mirror samples that were turned with the Omega-X nanometer machine tool. The diffraction characteristics of the mirror samples were tested by directing a 6328-A laser beam onto each mirror surface and measuring the power that was reflected into various diffraction orders. Table 1 shows the results of these tests for the three mirror samples. Samples 2 and 3 were machined six months later than Sample 1, after the Omega-axis rolling element bearings were replaced with hydrostatic oil bearings. These later samples showed high direct reflectivity values and considerable reductions in the amount of power reflected into the major diffraction orders. From the standpoint of reflectivity and light scatter, samples 2 and 3 were considered to be very adequate for Next Generation Telescope mirrors.

Table 1. Diffraction Characteristics of Aluminum Mirror Samples
Produced with The Omega-X Machine Tool

Measurement Location	Powermeter Reading, μ W			Percent of Total Power		
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Output Direct from Laser into Detector	1650	1600	1600	100	100	100
Direct Reflection from the Mirror ("Zero" Order)	1330	1400	1400	80.6	88	88
1st Diffraction Order Left of Zero Order	29	1.0	0.27	1.8	0.06	0.016
Right of Zero Order	33.5	1.0	0.23	2.0	0.06	0.014
2nd Diffraction Order Left of Zero Order	6.5	0.3	0.1	0.4	0.002	0.006
Right of Zero Order	4.5	0.3	0.1	0.3	0.002	0.006
3rd Diffraction Order Left of Zero Order	<1	NOT MEASURABLE		<0.1	--	--
Right of Zero Order	1.5	NOT MEASURABLE		0.1	--	--
Higher Orders	NEGLIGIBLE					

Summary

The features contributing most significantly to the unique performance of the Omega-X machine tool are the:

- Omega-X system - The stiffness and fineness of control that the Omega eccentric mechanism gives to the tool bar movement is essential to the accuracy of the surface finishes obtained. The solid support of the cutting tool by the tool bar and the stiff guidance of the tool bar through the pivoting linear bearing are key features of the system.
- Spindle - The spindle's accuracy, stiffness, and vibrationless rotary coupling drive all contribute to final surface quality.
- Machine tool base - The significant features of the machine tool base are the stiff, massive frame and the adjustable air mount suspension system.
- Machine control - The computer programmed control of the machine tool and the provisions for error correction and feedback make the best use of the servos, lead screws, and drive gearings that allow fine increments of machine tool movement.

Other considerations such as machining parameters, workpiece material characteristics, and the physical laws of motion will affect the quality of surface finishes produced. Tool edge sharpness, size and accuracy of nose radius, rake angles, feed per revolution, cutting depth, cutting speed, cutting oil viscosity and application, chip flow, and vacuum chip removal all individually contribute to the success of cutting operations and must be thoroughly understood. Some materials can be diamond turned to a fine finish while other materials cannot. Hardness, grain size, density, impurities and inclusions, and alloying elements all have some bearing on attainable results, but in many cases their effects are not well understood. A final consideration is that a machine tool is subject to minute natural frequency oscillations and undulations in an unknown number of directions. These movements need to be defined more clearly before any practical modification can be made to control them.