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# OPTICAM Machine Design

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**ABSTRACT**

Rank Pneumo has worked with the Center for Optics Manufacturing to design a multiple-axis flexible machining center for spherical lens fabrication. The OPTICAM/SM prototype machine has been developed in cooperation with the Center's Manufacturing Advisory Board. The SM will generate, fine grind, pre-polish and center a spherical lens surface in one setup sequence. Unique features of the design incorporate machine resident metrology to provide RQM (Real-time Quality Management) and closed-loop feedback control that corrects for lens thickness, diameter and centering error. SPC (Statistical Process Control) software can compensate for process drift and QA data collection is provided without additional labor.

## 1. MACHINE DESCRIPTION

The OPTICAM/SM is a horizontal spindle, multi-axis computer numerically controlled (CNC) machining center designed to automate spherical lens manufacturing (Figure 1). Operations include the rough generation, fine grinding, and pre-polishing of a spherical surface, as well as final centering, beveling and segmenting of the lens (Figure 2).[1] In-process metrology and closed-loop feedback control compensate for changes in tool, workpiece and machine conditions.

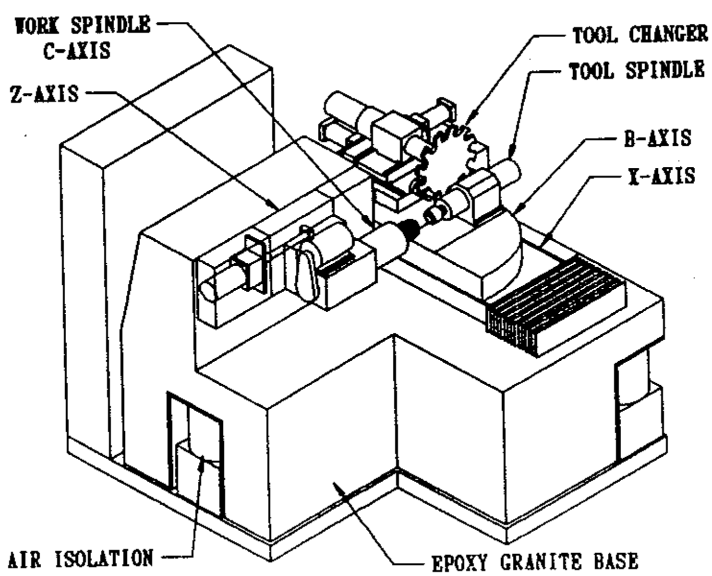


Figure 1. OPTICAM/SM multi-axis CNC machining center.



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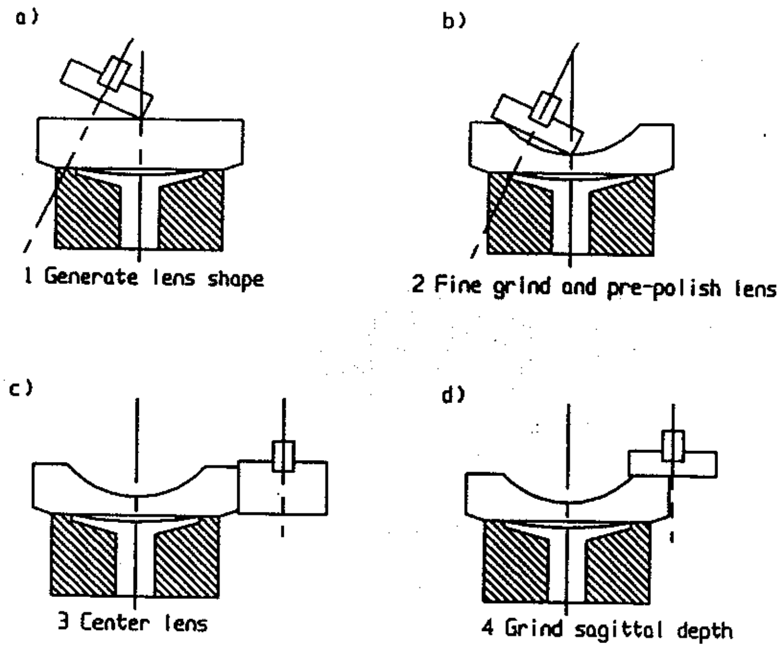



Figure 2. OPTICAM/SM (a) generates a lens shape, (b) fine grinds and pre-polishes, (c) center the lens and (d) grinds the sagittal depth.

OPTICAM/SM will produce concave or convex optical surfaces ranging from 5 mm radius of curvature to infinity. The machine will accommodate components from 10 to 100 millimeters in diameter and up to 100 millimeters in thickness. Rotationally symmetric part features and bevel surfaces of any angular orientation can be machined during the edging operation.

Although the ability of the machine to satisfy a specific tolerance requirement is process and part geometry dependent. OPTICAM/SM part tolerance capabilities are listed in Table 1.

| | |
|---|---|
| Diameter | ±0.010 mm |
| Center Thickness | ±0.010 mm |
| Runout | 0.0025 mm (FIM) |
| Sagittal (to flat) | ±0.005 mm |
| Power/Integrity | ±3/1 (fringes) |
| Surface Roughness | 500 Angstroms rms |
| Bevel Angle | ±0.01 degrees |

Table 1. OPTICAM/SM Part Tolerance Capability

### 1.1 Epoxy Granite Machine Base

Finite element techniques were used to design the base and isolation system for the machine. Finite Element Analysis (FEA) is a sophisticated modeling tool used to evaluate the static and dynamic behavior of machine components. FEA models can be used to perform 'what if' investigations of a component. This way, any deficiencies in the design can be spotted early in the design cycle where changes can be made before an expensive prototype model is built.

An example of a finite element model is shown in Figure 4. Various configurations of the model were evaluated to achieve the optimum stiffness and stability of the machine base.

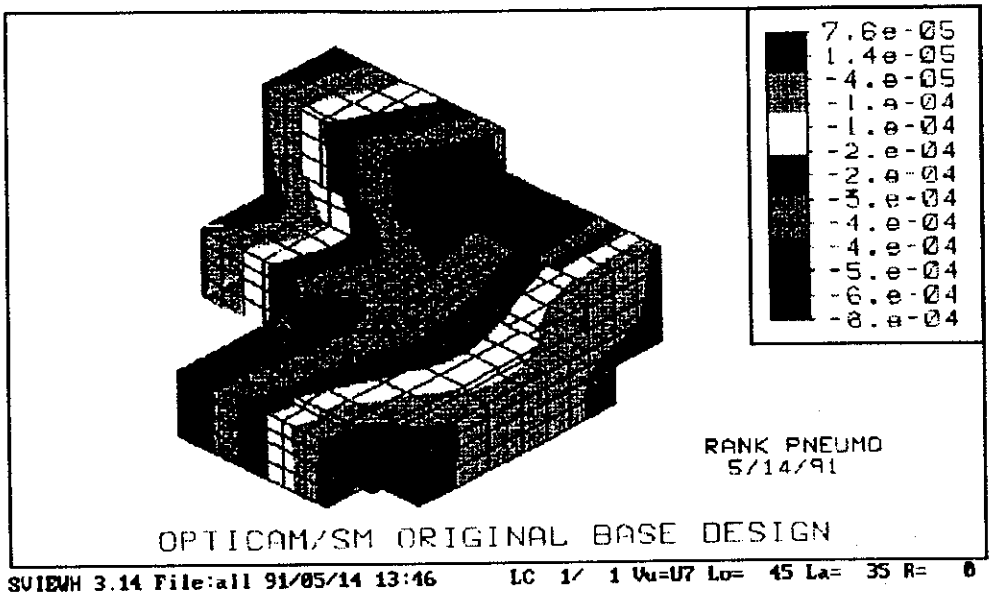
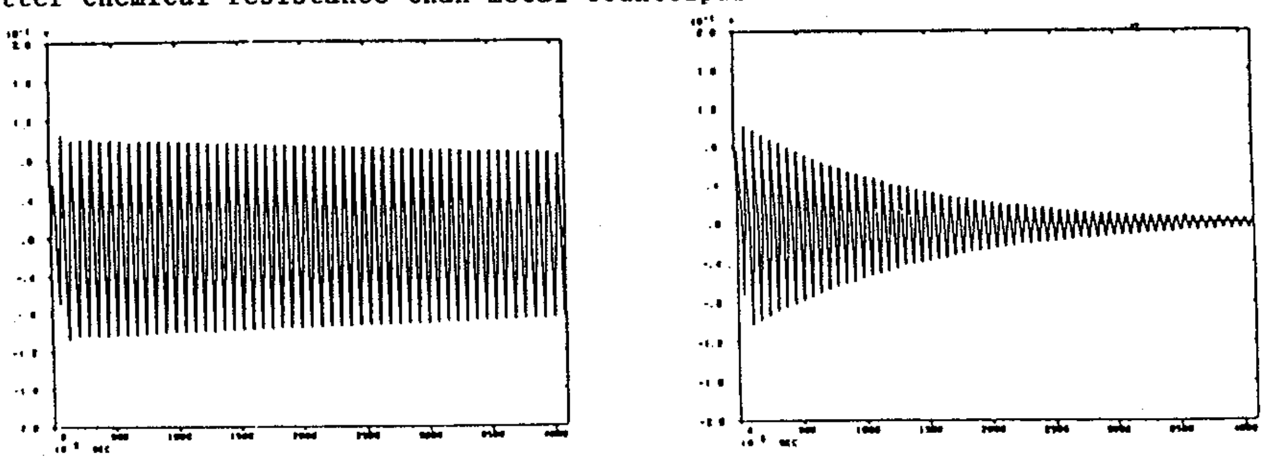



Figure 4. Finite Element model of the OPTICAM/SM showing the deflection of the machine base with three isolators.

The machine base will be fabricated of a castable synthetic granite material which offers superior dynamic stability and structural rigidity. The synthetic granite material (epoxy granite) is an aggregate mixture of fine to coarse granite particles and an epoxy resin. Epoxy granite provide superior damping characteristics when compared to cast iron or steel structures (Figure 3).[2,3,4] The material damping effects the vibrational modes of the machine structures. Damping is a measure of its resistance to vibration. The synthetic granite material provides excellent dimensional stability, thermal stability, vibration reduction and significantly better chemical resistance than metal counterparts.



a) cast iron b) epoxy granite

Figure 3. Comparison of damping in cast iron and epoxy granite.

The machine will have a pneumatic vibration isolation and leveling system, which can be setup as an active or passive system. This vibration system isolates the machine structure from floor vibrations at frequencies above 2Hz.

## 2.0 MACHINE AXES AND SPINDLES

Referring to the illustration in Figure 5, the X-axis is located on the right side of the base and has 400 mm of travel. The B-axis has 90 degrees of travel and is mounted on top of the X-axis. The tool spindle is mounted on the B-axis. The Z-axis is mounted on the base at the upper left and has 250 mm of travel. The work spindle, which is the C-axis, is cantilevered from the face of the Z-axis. The covers protecting the B-axis move beneath the work spindle. The tool changer is mounted over the X-axis.

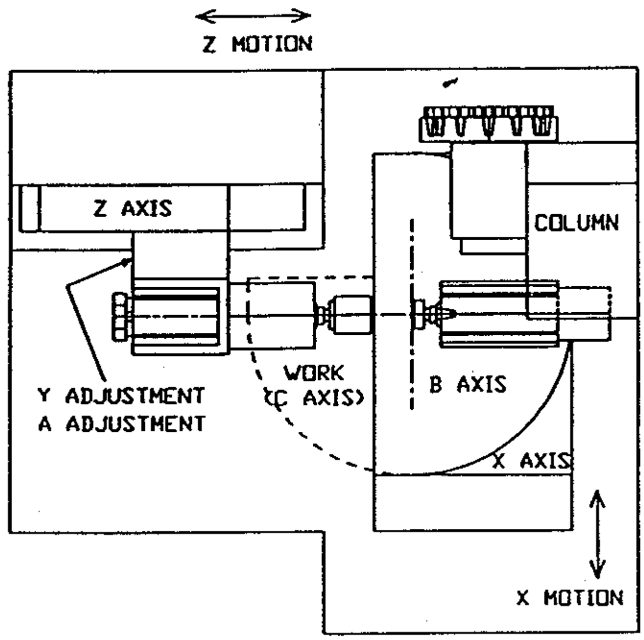



Figure 5. Top view of machine showing the relative location of the axes.

### 2.1 X and Z axes

The X and Z axes are modular slide units which mount onto steel plates grouted into the epoxy granite machine base. Both axes utilize a crossed roller bearing system to maximize rigidity and provide precise movement. The roller system is lubricated periodically by the central lubrication system. The axes are driven in translation by a precision preloaded ball screw and nut. The ball screw is driven by a direct coupled DC servo motor with tachometer feedback. The position loop is closed with a 0.1 micron resolution linear scale located at the front side of the slide beneath protective covers.

### 2.2 B-axis

The B-axis is a slide unit that mounts onto the X-axis carriage. This is a highly precise rotary axis with 90 degrees of travel. The top of the B-axis provides the mounting location for the grinding wheel spindle. The B-axis pivots about a pair of preloaded angular contact ball bearings. The periphery of the pivoting sector is supported on Teflon composite pads that slide on a precision ground surface. The B-axis is driven in rotation by a linear slide. The linear slide is driven by a preloaded precision ball screw, which in turn is driven by a DC servo motor. A pivoting block is mounted on the linear slide and engages a radial slot in the underside of the rotating carriage. As the ball screw turns, the linear slide moves, causing the sliding block to drive the pivoting carriage in rotation. The feedback is provided by an ultra-precision rotary encoder mounted concentric to the axis of rotation of the pivoting carriage. The angular resolution of the encoder is 0.144 arc seconds. Angular positioning is accurate to ±3.5 arc seconds and angular repeatability is accurate to ±2.0 arc seconds. An optional linear scale with 0.1 micron resolution is mounted to the linear slide which drives the rotary axis. The scale provides a 0.06 to 0.12 arc second variable angular resolution dependent upon axis position.

### 2.3 C-Axis (Work Spindle)

The work spindle is a bi-directional air bearing spindle with a speed range of 10-250 RPM. An optional ball bearing work spindle is also available. Work spindle alignment is provided by two alignment axes (Y and A axes) located between the Z-axis and the spindle. The spindle has an optional positioning mode that allows it to operate as an index head. With a cut-off wheel in the tool spindle, the index mode can segment lenses with a resolution 0.01 degrees. A segmenting operation is illustrated in Figure 6.

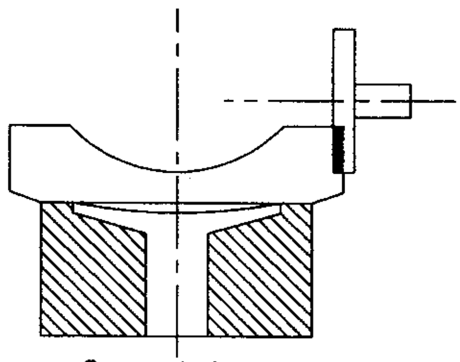

Segment lens

Figure 6. Segmenting of a lens with a cut-off wheel.

The spindle has a spring operated (push to release) drawbar and a taper for chucking the workpiece fixturing. A fluid connection is built into the spindle to provide air or vacuum to the work fixture. Position feedback from the C-axis is obtained from an encoder mounted directly in-line with the spindle. The work spindle is driven by a direct coupled DC motor-tachometer with an integral brake. The spindle is designed to be exchanged with replacement spindles without requiring major teardown or realignment of the machine.

### 2.4 Wheel (Tool) Spindle

The tool spindle is a foot mounted, precision air bearing motorized spindle with a speed range of 6,000 to 30,000 RPM. This speed range provides for a speed of 5000 surface feet per minute between the work and the tool. The spindle incorporates a spring actuated drawbar and a taper for automatic tool changing. Air is provided through the spindle for cleaning the chuck during tool changing. The spindle is driven by an integral high frequency AC motor rated at 11 KW at 30,000 RPM. The motor and the spindle bearings are water cooled to reduce thermal growth. A ball bearing tool spindle with the same operating specifications as the air bearing spindle is available as an option. This spindle mount is also designed to allow interchanging of tool spindles without requiring major teardown or realignment of the machine.

## 3.0 MACHINE CONTROL

An Allen-Bradley Series 9/240 Computer Numerical Control (CNC) is used as the machine control. The control is capable of parametric programming to permit data entry of part dimensional data in variable form. Part information, tooling, and material attribute data may be stored and accessed from the menu-driven environment. The controller is capable of making necessary process corrections based on probe sensory data. After completion of a cycle, probe sensory data will be compared with master input data. If a dimension exceeds the pre-set limits, the controller will calculate the corrective action required for the machine to return to the master input data set dimension, display the action recommendations, and go to the new position if commanded.

The operator interface includes a 12 inch color CRT display and a number of dedicated control switches and buttons. The machine is operated from within a menu-driven environment that aids the operator in entering required data. Display information includes the part program, tooling and global offsets, a graphical or numerical real-time axis movement and distance-to-go axis movement.

The controller will gather data from the part and tool probes and use this data to close the machining loop by altering variables in the part program to reflect changes in the part and tool. Quality inspection data will be collected and made available for upload to a host computer on demand.

System interfaces include an RS-232 serial communications port for program and data load/unload and supervisory control. There are ports for the part and tool probes. Discrete inputs and outputs are provided for relays, valves and switches and are connected to the control via fiber optic I/O ring network. The fiber optic I/O ring network provides superior noise immunity and high speed communication between components of the 9/240 CNC and the I/O devices. The fiber optic ring provides a simple, single cable connection between components. The minimum programmable increments are as follows:

| | |
|---|---|
| Angular increment | 0.001 degree |
| Linear increment | 0.001 millimeter |
| Linear infeed rate | 0.025 mm/minute |

Grinding wheel dimensions are measured by a touch trigger probe mounted near the tool spindle. The probe simulates a coordinate measuring machine that enables fully automated inspection using geometric data input in the master data set. The tool probe will measure tool diameter and length and eliminates the need to preset tools prior to loading them into the tool changer's storage area.

The workpiece is measured by another probe mounted on a standard tool shank and stored in the tool changer. Part probing will be used to verify center thickness, diameter, runout and spherical radius.

## 4.0 ADDITIONAL EQUIPMENT

### 4.1 Tool Changer and Tool Dressing

An automatic tool changer is provided on the machine. Tools up to 76 mm in diameter can be automatically exchanged between the tool spindle and a tool storage area. These tools will be fitted with tapered shank adaptors. Storage is provided for up to 12 tools, including work probes. Tools will be manually loaded into the tool storage device, where they will be held by spring actuated clips. Grinding wheels will be dressed and trued by a tool mounted in place of the workpiece.

### 4.3 Flood Coolant System

The coolant system is a self-contained unit that can be removed for service or fluid change. The coolant temperature is held constant to $\pm 1°F$ and is adjustable within a 65-75°F range. This system is compatible with either oil or water based coolants. Maximum coolant flow rate will be 5 gallons per minute. The coolant is filtered by a three stage system. Coolant returning from the machine first dwells in a settling tank before being circulated through a centrifuge to remove the bulk particles. In the final stage, a series of filters that terminate in a 3 micron filter remove fine contaminants from the coolant returned to the machining area.

### 4.4 Floating head spherometer

A floating head spherometer is mounted adjacent to the tool spindle and is brought into contact with the workpiece to measure it's radius of curvature. This instrument has a long stroke linear probe that provides a digital readout of the sagittal depth (height) of the workpiece. Information from the probe can be used to close the machining loop. The floating head spherometer allows more accurate workpiece radius of curvature measurement and decreases the measurement cycle time.

## 5.0 CONCLUSIONS

In the future, Rank Pneumo will apply the experience and expertise gained in the development of the OPTICAM/SM to several other machine models to be developed in future C.O.M. programs. The OPTICAM/PM will be a five axis CNC ultra-precision grinding machine for prism manufacturing and the OPTICAM/AM will concentrate on the rapid production of aspheric optics. Although these machines will use some design concepts similar to the OPTICAM/SM, the unique requirements of each machine will lead to significant challenges in the future developments of advanced machinery for the production of optical components.

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