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Engineering and
Equipment

MASTER

E. I. du Pont de Nemours and Company, Incorporated
Engineering Department
Engineering Technology Laboratory
Wilmington, Delaware

ULTRA PRECISION MACHINE TOOL ELEMENTS AND MACHINING PROCESSES

T. G. Lewis

Work Performed under Subcontract 51Y32100-C
with

Union Carbide Corporation
Nuclear Division
Y-12 Plant
Oak Ridge, Tennessee

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** under **U. S. GOVERNMENT Contract W-7405 eng 26**

**UNION
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ABSTRACT

Engineering principles, as they apply to ultraprecise machining processes, have been investigated by Du Pont engineering technology personnel as a part of a continuing program in the study of machine tools. In this machining process, maximum deviation from an idealized shape and size was not to exceed a few microinches.

Two phases of the study are reported: (1) to develop an experimental research machine that would be limited to turning solid hemispheres, but would deviate no more than 25 microinches from a four-inch diameter at any point on the hemisphere; (2) to study the effects of work hardness and associated parameters on the machine tool elements and processes developed in Phase I, to apply multistage operations to machining a sphere with a deviation not to exceed five microinches, and to develop a new and more versatile experimental machine that would be able to fabricate more delicate and complex test pieces.

This study was culminated in the development of a new experimental machine tool called the "hemishell turning machine" which "represents the epitomy in ultraprecision machining technology".

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PROGRAM SCOPE

The work described in this report has been carried out by Du Pont engineering technology personnel for the Oak Ridge Y-12 Plant, (a) under subcontract 51Y32100-C with the Union Carbide Corporation—Nuclear Division.

This study is part of a continuing program in the study of machine tools—their theory and operation—with particular attention to analyzing the behavior of machine-tool elements in relation to their overall performance. The objective of the program, of which the work herein reported is a part, is to study engineering principles as they apply to ultraprecise machining processes where the maximum deviation from an idealized shape and size is not to exceed a few microinches.

The study was planned in two phases. For the initial phase, the objective was to develop an experimental research machine that would not deviate more than 25 microinches from a four-inch diameter at any part on a hemisphere. To reduce the number of variables, it was agreed to limit the work to a study of machining processes applied to a simple, comparatively sturdy shape; specifically, a solid hemisphere of relatively soft material (Type 2014 aluminum alloy) having a generously flanged cylindrical base for simple, rigid mounting. The highly specialized experimental machine developed for this phase of the study is known as the "hemisphere turning machine".

For the second phase, three distinct blocks of work were undertaken:

1. Ultraprecise machining of solid hemispheres made of relatively hard materials (such as sintered tungsten and Type AISI 304 stainless steel) to study the effects of work hardness and associated parameters.
2. Ultraprecise machining of solid spheres made of Type 2014 aluminum alloy to study multistage operations.
3. Ultraprecise machining of relatively delicate shapes of soft material (such as hollow hemispheres or hemishells made of Type 2014 aluminum alloy). The goal of this effort was to study the effects of a more intricate shape combined with multistage machining operations. This study included the development of a new experimental machine tool, called the "hemishell turning machine", which, it is felt, represents the epitome in ultraprecision machining technology.

(a) The Y-12 Plant is operated for the United States Atomic Energy Commission by the Union Carbide Corporation.

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PHASE I

EXPERIMENTAL HEMISPHERE TURNING MACHINE

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INTRODUCTION

As indicated in the Program Scope, Phase I concerned the development of an experimental research machine limited in capability to turning solid hemispheres. (A sphere, representing the ultimate in dimensional simplicity, was regarded as the ideal proofpiece in establishing both the criteria of the machine design and in evaluating performance.) The goal set for the Phase I machine, stated in its simplest terms, was the development of a machine capable of turning an aluminum alloy hemisphere, four inches in diameter, that deviated at no point more than 25 microinches from that diameter. To meet such a requirement, the following machine-tool design specifications were formulated:

1. The rotational accuracy of both work and cutterhead spindles should be within five microinches.
2. The thrust accuracy of both work and cutterhead spindles should be within five microinches.
3. The friction coefficient for both spindles should be exceedingly low, about 5×10^{-6} or less.
4. The dynamic balance of the work spindle should afford rotational accuracy up to 2,000 rpm within five microinches total deviation from the axis of rotation.
5. The static balance of the cutterhead spindle should be less than one inch per pound.
6. The tool-feed mechanism should be capable of feeding in increments of five microinches.
7. All sources of vibration, including all motor drives, should not be greater than five microinches peak to peak measured between the work and tool holder.
8. The axial and radial stiffness of both the work and cutterhead spindle should be such that the maximum rate of deflection will not exceed five microinches per pound.

The basic concept of the machine tool is shown in Figure 1. The machine tool essentially consists of a work spindle with its axis of rotation noted as y-y, and a cutterhead spindle with its axis of rotation noted as x-x. These axes intersect at

zero, the center of the hemisphere. The cutterhead spindle provides a mounting for the cutting tool and, when rotated about axis $x-x$, will generate the path AB, the directrix for the hemisphere. As the cutting tool moves along the path AB, the work spindle on which the work is mounted rotates about axis $y-y$. Thus, a hemisphere is generated.

This report describes the design considerations necessary for the development of the machine tool, the procedures followed in its fabrication, and an evaluation of its capabilities.

DESIGN CONSIDERATIONS

SPINDLE ASSEMBLIES

Air Bearings

Of prime importance in meeting the rigorous design specifications for the hemisphere turning machine was the selection of the type of bearing to be used for both radial and thrust loads in the work and cutterhead spindle assemblies. The air-lubricated hydrostatic bearing was chosen for its low friction characteristics, its accuracy potential, and because it generates little heat, a factor of the utmost importance in ultraprecision machining. The only inherent disadvantage of air bearings is that their stiffness characteristic is generally less than that of other types of bearings, but it is a disadvantage generously compensated for and well worth the compromise.

The design of the hydrostatic air bearings was developed from information gathered during past work on various Du Pont-developed ultraprecision machine tools, which included the experimental testing of a two-inch by four-inch flat air bearing. The resulting air-bearing designs are somewhat different from those of conventional air bearings. The lubricating air film is supplied through a structure of Graphitar G-2, a graphite-carbon sintered material.^(b)

Figure 2 shows a plot of the variations between gas-film thickness and the unit pressure of the gas film for the two-inch by four-inch experimental flat bearing. Two hundred pounds per square inch was selected as an adequate supply pressure to provide the necessary stiffness to the gas bearings.

(b) Supplied by the US Graphite Company.

Figure 1. HEMISPHERE TURNING MACHINE.

From the 200-psi curve in Figure 2, it may be noted that the change in film thickness with change in loading is about 2 microinches/psi of bearing surface when the film thickness is 100 microinches. The design of the 3-inch-diameter by 3 3/4-inch-long spindle bearings for this equipment is at this point on the curve.^(c)

Constant forces, such as gravitational forces, were not considered significant in the design of the spindle assemblies. The only force considered was that generated by

Figure 2. GAS-FILM THICKNESS AS A FUNCTION OF THE AVERAGE UNIT PRESSURE IN THE FILM. (Gas-Lubricated Bearing; 2" x 4" Flat Shoe; Graphitar G-2; Nitrogen Gas Supply)

the cutting tool. Experience has shown that this force has a maximum variation of one pound in this type of machining system. All design calculations, therefore, were made for a one-pound force acting at the tool position.

The force system considered to be acting on the cutterhead spindle is represented in Figure 3. It is noted that when a one-pound force acts at the cutting tool, a 1.76-pound force acts at the front bearing and a 0.76-pound force at the rear bearing. The deflection of the air films is calculated from these resulting forces; thus:

- (c) For reasons of economy and time, it was decided that the spindle dimensions should conform to the dimensions of the lapping equipment that was already on hand. Any lack of stiffness in the spindles would be compensated for by the design of the thrust bearings.

(a) Loading of the Gas Bearing for the Cutterhead Spindle

(b) Loading of the Gas Bearing for the Work Spindle

Figure 3. FORCE SYSTEMS ACTING ON THE CUTTERHEAD AND WORK SPINDLES.

Let:

- A represent the effective projected area of the journal,
- d the diameter of the journal,
- l the length of the bearing,
- a the stiffness coefficient (from the curve on the experimental bearing),
- Y_{tc} the deflection at the tool position of the cutterhead,
- Y_{tw} the deflection at the tool position of the work,
- Y_{fc} the deflection at the centerline of the front bearing in the cutterhead spindle,
- Y_{rc} the deflection at the centerline of the rear bearing in the cutterhead spindle,
- Y_{fw} the deflection at the centerline of the front bearing in the work spindle,

- Y_{rw} the deflection at the centerline of the rear bearing in the work spindle,
 W_{fc} the load at the centerline of the front bearing in the cutterhead spindle,
 W_{rc} the load at the centerline of the rear bearing in the cutterhead spindle,
 W_{fw} the load at the centerline of the front bearing in the work spindle,
 W_{rw} the load at the centerline of the rear bearing in the work spindle,
 W_{tc} the load at the tool position in the cutterhead, and
 W_{tw} the load at the tool position on the work.

Two projected areas are considered in these calculations: (1) that area opposed to the load, and (2) that area adjacent to the load. The area adjacent to the load will have a lesser force inasmuch as the deflections cause a decreasing pressure in the air film. Therefore, for calculation purposes, the effective projected area is equal to two times the diameter times the length of the journal bearing.

Given:

$$d = 3.0 \text{ in}; W_{fc} = 1.76 \text{ lbs}; W_{fw} = 1.57 \text{ lbs};$$

$$l = 3.75 \text{ in}; W_{rc} = 0.76 \text{ lb}; W_{rw} = 0.57 \text{ lb};$$

$$A = 2 dl = 2 \times 3.0 \text{ in} \times 3.75 \text{ in} = 22.5 \text{ in};$$

$$a = 2 \mu\text{in/lb/in}^2.$$

Then:

$$Y_{fc} = \frac{aW_{fc}}{A} = \frac{2 \times 10^{-6} \times 1.76}{22.5} = 1.5 \times 10^{-7} \text{ in/lb};$$

$$Y_{rc} = \frac{aW_{rc}}{A} = \frac{2 \times 10^{-6} \times 0.76}{22.5} = 6.8 \times 10^{-8} \text{ in/lb};$$

$$Y_{fw} = \frac{aW_{fw}}{A} = \frac{2 \times 10^{-6} \times 1.57}{22.5} = 1.4 \times 10^{-7} \text{ in/lb};$$

$$Y_{rw} = \frac{aW_{rw}}{A} = \frac{2 \times 10^{-6} \times 0.57}{22.5} = 5.0 \times 10^{-8} \text{ in/lb.}$$

With reference to the loading diagram (Figure 3) and the calculated deflections at the centerline of the bearings, the deflections measured at the tool position are calculated as:

$$Y_{tc} = \frac{19.9 Y_{fc} + 8.6 Y_{rc}}{11.3} = 3.1 \times 10^{-7} \text{ in/lb.};$$

$$Y_{tw} = \frac{17.9 Y_{fw} + 6.6 Y_{rw}}{11.3} = 2.2 \times 10^{-7} \text{ in/lb.}$$

Thus, the sum of $Y_{tc} + Y_{tw}$ represents the maximum total radial deflection measured between the tool and the work resulting from the deflection in the air films of both spindles. The sum equals 0.55×10^{-6} inch.

In considering thrust loads, only the work spindle's load is critical. The calculated deflection in the air film for unit loading is:

$$Y_{thrust} = \frac{aW}{A} = \frac{2 \times 10^{-6} \times 1}{22.4} = 9.0 \times 10^{-8} \text{ in/lb.}$$

The cutterhead spindle thrust bearing has an area of 35.3 square inches and, therefore, a deflection per unit loading less than the work spindle. It is, consequently, considered insignificant.

Self-Aligning Radial Bearings - The required air-film thickness of 100 to 200 micro-inches imposed a critical alignment problem for the journal bearings. The alignment error resulting from the initial assembly, distortion from loading, and distortion from thermal effects makes it impractical to use fixed journal bearings. Consequently, three self-aligning shoes placed 120 degrees about the guiding surface comprise the journal bearing, as shown in Figure 4. Such a design permits the bearing components to seek the optimum positions, thereby compensating for the various distortions.

A flexure (Figure 4, Item 104C) was designed to attach two of the three shoes to the master shoe. This arrangement offers restraint to any rotary motion about a radial axis that could be caused by bearing contamination or friction, thus eliminating the possibility of bearing damage.

Thrust Bearings - The design of the thrust bearing was purposely oversized to offer restraint to the bending of the spindles.

Two designs to control the air-film thickness in the thrust bearings were developed—one for the cutterhead spindle, the other for the work spindle. For the cutterhead spindle, which has a thrust-bearing area of approximately 35 in^2 and a designed air-film pressure of 100 lbs/in^2 , a thrust force of 3,500 pounds was calculated. In a free state, the fit of the thrust bearing (Figure 4, Item 103D) requires no clearance. When lubricating air is supplied to the bearing, the pressure developed by the film produces strain within the shaft and associated components to provide a calculated clearance of 200 microinches.

Control of the air-film thickness in the work spindle is provided by a preloaded flexure (Figure 4, Item 102B), a part of the rear thrust bearing. The fitup of the spindle assembly is such that, when the thrust nut (Item 103C) is properly adjusted, a 0.006-inch deflection occurs in the flexure, producing a thrust load of 2,200 pounds. With a 100-psi air film and 22 in^2 of thrust-bearing area, the total force of the air film equals the force of the flexure. The loads so imposed by this arrangement cause strain in the shaft and associated thrust-bearing components to produce a clearance of 100 to 200 microinches.

Spindles

The required structural design of the spindles prevented the use of a single, simple loading concept for calculating the deflection. As a compromise, two simple concepts of loading were assumed—free-beam and guided-beam loading. Past experience had shown that the actual deflection per unit loading would fall between the values predicted in each loading concept.

Cutterhead Spindle - The first loading model considered for the cutterhead spindle is a free beam, shown in Figure 5, Case 1. A beam supported in this manner will have minimum stiffness or, to put another way, maximum deflection.

The deflection resulting from bending is calculated as follows:

Let:

Y	represent the deflection,
W_{tc}	the load at the test position (unit loading),
C	the distance from the tool position to the centerline of the front bearing,
E	the modulus of elasticity (in this case 3×10^7), and
I	the moment of inertia of the section.
L, M, N, and P	represent the distances measured along the beam, as noted in Figure 5.

Figure 4. BEARING ASSEMBLIES.

(a) Free Beam

(b) One End Guided

Figure 5. BENDING OF THE CUTTERHEAD SPINDLE.

Then:

$$Y = \frac{W_{tc} (C_c)^2}{3EI} (C_c + L_c), \text{ or}$$

$$Y = \frac{1 \times (8.6'')^2}{3 \times 3 \times 10^7 \times 3.98} (8.6'' + 11.3''),$$

$$= 4.12 \text{ } \mu\text{in/lb.}$$

The case just presented, however, is not a completely true situation. The spindle's thrust bearing offers restraint to bending, so the guided-beam model (shown in Figure 5, Case 2) is somewhat representative of this situation:

$$Y_{fc} = \frac{W_{fc} M_c^2 N_c^2}{12EI P_c^3} \times (3P_c + N_c), \text{ or}$$

$$Y_{fc} = \frac{1.75 \text{ lbs} \times (4.4'')^2 \times (11.3'')^2}{12 \times 3 \times 10^7 \times 3.98 \times (15.7'')^3} \times (3 \times 15.7'' + 11.3''),$$

$$= 0.72 \text{ } \mu\text{in/lb.}$$

The deflection is given at the centerline of the front radial bearing. The deflection at the tool positions is calculated from:

$$Y_{tc} = \frac{P_c \times Y_{fc}}{N_c} = \frac{15.7 \times 0.72 \times 10^{-6}}{11.3''} = 1.0 \text{ } \mu\text{in/lb.}$$

Work Spindle - Deflection as a result of bending in the work spindle is calculated as follows:

The minimum restraint to bending will be given when the structural arrangement is considered as a free beam, shown in Figure 6, Case 1. This condition is represented by:

$$Y_{tw} = \frac{W_{tw} (C_w)^2}{3EI} (C_w + L_w),$$

$$= \frac{1 \times (6.6)^2}{3 \times 3 \times 10^7 \times 3.98} \times (6.6'' + 11.3''),$$

$$= 2.2 \text{ } \mu\text{in/lb.}$$

As with the cutter head, some restraint to bending is afforded by the thrust bearing. The structural arrangement representative of this condition is shown in Figure 6, Case 2, and is expressed by:

$$Y_{fw} = \frac{W_{fw} M_w^2 N_w^2}{12EI P_w^3} (3P_w + N_w),$$

(a) Free Beam

(b) One End Guided

Figure 6. BENDING OF THE WORK SPINDLE.

$$\begin{aligned}
 &= \frac{1.57 \times (4.4'')^2 \times (11.3'')^2}{12 \times 3 \times 10^7 \times 3.98 \times (15.7'')^3} \times (3 \times 15.7'' + 11.3''), \\
 &= 0.65 \text{ } \mu\text{in/lb.}
 \end{aligned}$$

The deflection is given at the centerline of the front radial bearing. Converting to deflection at the tool gives:

$$Y_{tw} = \frac{P_w \times Y_{fw}}{N_w} = \frac{15.7" \times 0.65 \times 10^{-6}}{11.3"} ,$$

$$= 0.9 \text{ } \mu\text{in/lb.}$$

Total Radial Deflection

Table 1 summarizes the calculated radial deflections in both the bearings and spindles as a result of a one-pound load acting at the cutting-tool position. In brief, the maximum total deflection of the cutterhead and work-spindle assemblies is 6.8 microinches; the minimum, 2.4 microinches. Thus, if radial forces resulting from cutting are controlled to about one pound, the relative displacement between the tool and work will lie somewhere between these extremes.

Table 1
CALCULATED RADIAL DISPLACEMENT AT THE TOOL POSITION

	Deflection as a Free Beam (μin)	Deflection as a Guided Beam (μin)	Deflection in Gas Film (μin)	Maximum Deflection (μin)	Minimum Deflection (μin)
Cutterhead Spindle	4.1	1	0.31	4.41	1.3
Work Spindle	2.2	0.9	0.22	2.42	1.1

Thrust deflections in the work and cutterhead spindle assemblies are so small that they are considered to be insignificant.

SPINDLE DRIVES

The prime consideration in selecting the work-spindle drive is the lowest possible vibration. The most satisfactory equipment found for this application was the Select-A-Speed drive, ^(d) a motor-generator unit powering a specially constructed one-horsepower, DC motor. This unit produces a maximum peak-to-peak vibration

(d) Manufactured by the Louis Allis Company.

of only 50 microinches. Using special vibration-isolation mounts^(e) which have an attenuation factor of 20 to 1, the 50-microinch peak-to-peak amplitude at the motor is reduced to 2 1/2 microinches at the critical part of the machine. The work spindle is powered through the use of crowned pulleys and a 1/64-inch-thick by 1-inch-wide flat, endless woven belt. Selection of the belt weight is critical, since belt flutter produces vibration in the work spindle.

The prime objective in the design of the cutterhead spindle drive is angular motion without vibration. Conventional gear drives are generally unsatisfactory for this type of application.

The cutterhead spindle is powered by a 1/6-horsepower variable-speed drive unit^(f) under the trade name of Ratiotrol, shown in Figure 7. The motor, with one jack shaft (Item 106C), is mounted on a sub-base (Item 105B) that is, in turn, mounted to the base casting, again using the special vibration-isolation mounts. Output from the jack shaft is coupled to a vertically mounted 31-inch-long screw (Item 111C), whose linear motion is used to drive the cutterhead spindle (Item 100A). The linear motion of the screw is converted to angular motion in the cutterhead spindle by a 0.020-inch-thick by 0.500-inch-wide steel belt, Item (L). One end of the steel belt is attached to the nut (Item 111E) on the drive screw, and the other end is weighed with several pounds of lead. The belt rides on a 12-inch-diameter sheave (Item 108C) mounted on the rear of the cutterhead spindle. With this arrangement, it is possible to get about 270 degrees of vibrationless rotation in the cutterhead spindle.

With a maximum work-spindle speed of 2,000 rpm, the maximum speed of the cutterhead spindle produced 0.001 inch of travel on the surface of a four-inch-diameter hemisphere per revolution of the workpiece. With a tool having a straight cutting edge oriented tangent to the spherical surface, scalloping of the surface is held to less than one microinch from a true spherical surface.

CUTTERHEAD

The cutterhead design has two pertinent features: (1) the feed mechanism comprises a differential screw, and (2) the fitup of the lapped surfaces requires a clearance of 10 to 20 microinches. The differential-screw assembly employs 28 and 32 threads/inch. This ratio produces a 0.0045-inch advancement of the tool for each revolution of the nut. Thus, rotation of the nut in 1/2-degree increments advances the tool approximately six microinches.

(e) Manufactured by the Lord Manufacturing Company.

(f) Manufactured by the Boston Gear Works.

Figure 7. CUTTERHEAD DRIVE.

The smaller the clearances, the more precise the control of the tool position. With a clearance of 10 to 20 microinches and using grease as a lubricant, the cutterhead assembly is quite rigid.

AIR-SUPPLY SYSTEM

Figure 8 is a block diagram of the oilless air-compressor-type supply system.^(g) All components are commercially available except the air filter, which was especially designed for this machine.

Figure 8. COMPONENTS OF THE AIR-SUPPLY SYSTEM.

The hemisphere turning machine requires compressed air at a flow rate of 5.25 scfm at 150 psig. To meet these requirements, two commercial compressors,^(h) were purchased. Each of these units will deliver 4 scfm of oil-free air at 175 psig.

The bearing surfaces in the hemisphere turning machine are very reactive to moisture; therefore, it is necessary to remove excess moisture to prevent bearing deterioration.

(g) Early work on this project was done using nitrogen as the bearing gas. Past experience with gas bearings, however, has shown that there is little difference in bearing operation when using either air or nitrogen as the lubricating gas.

(h) Manufactured by the Bell and Gossett Company, Model D-1715-30-T.

A commercial air dryer⁽ⁱ⁾ is used. At 175 psig, this unit removes excess moisture to a level where the dew point is about -5° F at atmospheric pressure.

Experience has shown that the desiccant in the air dryer produces a small amount of contamination in the form of a powder that is harmful to the gas bearing. An air filter (Figure 9) made of Graphitar G-2 was provided to eliminate this contamination. The filter area is about four times the total bearing area of the hemisphere turning machine. This arrangement produces an approximate pressure drop of 20 percent in the supply pressure.

Two stages of pressure regulation are used: (1) from supply pressure to 125 psig; (2) from 125 to 100 psig for the work spindle and from 125 to 80 psig for the cutter-head spindle. All pressure regulators were supplied by a commercial vendor.⁽ⁱ⁾

GEOMETRICAL MEASURING SYSTEMS

Two kinds of measurement capability are required with this type of machine tool: (1) measurement of the geometry of the hemisphere; (2) measurement of the dynamic balance of the work spindle. A white-light interferometer system using microscope viewing was devised that satisfies both measurement requirements.

An isometric drawing of this system is presented in Figure 10. The system consists of three white-light interferometers arranged in a translating system. This translating system permits the two straight-line motions in a horizontal plane required to transfer the gage-block dimension, which governs the dimension of the hemisphere, to the diameter of the hemisphere. A third straight-line adjustment in a vertical plane allows one of the interferometers to be used as part of the dynamic balancing system.

In order for the interferometer measuring system to perform reliably in the micro-inch range, a number of extraneous effects had to be controlled or eliminated from the system, such as variable forces or temperatures acting on the interferometer carriage. Consideration for these effects was emphasized during the design of the system.

In Figure 10, it can be seen that the interferometer carriage is suspended on air films. These films possess extremely low frictional coefficients. As a result, the strains resulting from the varying forces of adjustment of the undercarriage are almost completely divorced from the interferometer carriage. The only apparent force changes acting on the interferometer carriage arise from the wires supplying

(i) Sold by the Van Products Company, Model 25.

(j) The Moore Products Company, Model 40-300.

an electric current to the interferometer lamps and the hose which supplies air to the air bearings. The wire and hose are quite limber, however, and as yet no data variations have been traced to them.

Temperature effects on the interferometer carriage has been minimized by covering critical exterior surfaces with a one-inch-thick sheet of foamed plastic. Thus, air drafts from the air-conditioning systems and the heat radiated by operating personnel are controlled to the extent that the drift rate during measurements is about 0.2 microinch/min. This rate of change is quite compatible with the operating requirements of the system.

FABRICATION

LAPPING

The critical machining operations were confined mainly to the fabrication of the journal and thrust bearings of the spindles and the cutterhead. In general, all critical surfaces were ground to a tolerance of 100 to 200 microinches, leaving 200 to 400 microinches of material for lapping. Sizes in the microinch range were established by fitting one part to another, rather than working to a specific dimension using gage blocks.

Lap Design

Figure 11 shows two laps of the type used to refine the bearing surfaces of the spindle assemblies. The face lap was used on the thrust face of the spindles and the cylindrical lap on the journal surfaces. These journal surfaces are indicated schematically in Figure 12. The attainment of the precise geometry necessary in these guiding surfaces requires more than ordinary attention to lap design, particularly in regard to the structural stiffness of the lap, selection of lap materials, and lap adjustment.

It has been observed that the force in hand-lapping operations seldom exceed 10 psi. If the total area to be lapped is known, it is possible to compute the total force acting between the lap and the work. To do this, it is assumed that the worst possible conditions for lapping exist at the commencement of a particular lapping operation. It is also assumed that the geometry of the work surface is such that the most distant parts of the work surface will engage the lap surface. It is the object of lap design to have a structural stiffness to resist strain under these conditions of loading so that deflection does not exceed the desired deviation from a true surface. For example, if the face lap would contact a face at the 6 1/4-inch diameter, giving 22 square inches of surface, the total load would be approximately 220 pounds. Deflection here should not be more than 10 microinches. The face lap shown in Figure 11 meets these conditions. Laps with less rigidity prolong the

Figure 9. THE AIR FILTER.

Figure 10. HEMISPHERE MEASURING SYSTEM.

lapping operation and, in extreme cases, may make the lapping operation uncontrollable. The same conditions are assumed for the cylindrical lap; ie, when beginning to lap journal surfaces, local contact will exist in positions 180 degrees apart.

The most satisfactory lap material to use in any given application depends on the work material. In the case of the spindles, which were hardened steel, cast iron or Meehanite GB make excellent lap materials.

The face lap obviously requires no adjustment; the cylindrical lap, on the other hand, does. Conventional cylindrical laps are usually made adjustable by splitting the lap along a line parallel to the axis of the cylinder. This method of diameter adjustment is most undesirable in precision applications because the adjustment feature lessens lap stiffness. The cylindrical lap shown in Figure 11, however, produces maximum stiffness with adjustability. It may be seen that the Meehanite GB sleeve is tapered 0.02 inch through four inches of length. Adjustment is made by moving the sleeve axially within the holder.

Figure 11. TWO TYPES OF LAPS USED TO REFINE THE BEARING SURFACES.

The lapping operation is progressive, starting with Size 6 diamond powder, working through Size 3, and finishing with Size 1. Olive oil is used as the vehicle, except when lapping Graphitar G-2.

Lapping Procedures

Journal Bearings - The initial operation is to refine all spindle bearing surfaces with Size 6 powder. The bearing shoes are lapped on the dummy shaft having the same diameter as the spindle to within ± 20 microinches. Lapping procedures for the shoes are slightly different in that the diamond powder is suspended in alcohol (rather than olive oil), is sprayed onto the dummy shaft, and is permitted to dry before the lapping process begins. After evaporation of the alcohol, dry lapping is performed on the shoes. This modification in the lapping process is necessary to prevent contamination of the porous Graphitar G-2 with oil, which is difficult to purge from the Graphitar G-2 and which will cause erratic bearing operation.

Spindles -

Work Spindle - The spindle test rig shown in Figure 12 is set up on a surface plate. The lower two of the three bearing shoes for each bearing are set in place on each journal surface. Air at about 15 psi is supplied to each shoe

Figure 12. SPINDLE TEST RIG FOR CHECKING JOURNAL SURFACES.

through the spherical seats in the identical way air is supplied in the completely assembled spindle. This force supports the spindle. A toolmaker's knee is placed on the surface plate with the face of the knee oriented at a position normal to the axis of the spindle. The surface plate is adjusted with about $1/2$ to 1 degree of tilt; the thrust-face end of the spindle is on the high side of the plate. A precision steel ball with a $3/8$ to $1/2$ -inch diameter is placed between the conical center left in the spindle from the turning and guiding operations and the toolmaker's knee. When air is supplied to the shoes, gravitational force causes the spindle to float toward the knee. The ball will make point contact with the face of the knee. This arrangement provides a thrust bearing for testing during the lapping operations.

Geometrical evaluation of the journal-bearing surfaces is the next step. With reference to Figure 12, an electronic displacement indicator, or its equivalent,

is positioned at the top dead center at one end of one of the journal-bearing surfaces. A reference mark is placed on the periphery of the nose of the spindle to establish the angular position of all data to be taken. The spindle is then slowly turned by hand at about 1/2 to 1 rev/sec. Note is made of the runout of the surface, as indicated by the displacement indicator, and a polar plot is recorded for the axial position. Similar plots are recorded for the opposite end of the journal surface, as well as for both ends of the other journal surface. If a reasonably good grind of the journal surface has been made, it is normal to expect surface deviations in the order of 50 micro-inches.

If a plot is taken at the axial center of each journal surface, the surfaces generally show smaller deviations. It should be remembered, however, the self-aligning feature of the design makes each journal surface rotate about a point at the axial center of the surface. The deviations recorded at this position are entirely those caused by out of roundness, while those recorded at the ends of the journal surfaces result from out of roundness and whatever "crank motion" that may exist. The objective of all subsequent lapping is to remove all of this crank motion and, at the same time, make the cylindrical surface truly round.

A study of the polar plots will indicate the direction of the crank motions in each journal surface, and it will be obvious where metal must be removed to eliminate it. Localized lapping is performed. This action leads to a somewhat oval condition at that axial position. The subsequent application of the cylindrical lap, however, will bring the surface back toward a true cylinder. Thus, by displacement indicating, plotting, localized lapping, and full cylindrical lapping, a condition is reached where the indicated errors are about 20 microinches.

The entire procedure just described is repeated with Size 3 diamond powder. At the completion of this step, indicated errors in the order of 5 microinches may be expected. The final step with Size 1 powder will yield less than a 5-microinch error, depending on a number of such factors as temperature control, interpretation of data, variations in abrasion resistance of work materials, and the skill of the operator.

The face lap shown in Figure 11 is used for refining the thrust face. The same progressive process of lapping is applied, with testing and localized lapping and application of the full face lap until the required geometry is attained. When completed, this face should also have a deviation of only 5 microinches or less.

Cutterhead Spindle - Lapping of the cutterhead spindle is precisely the same as for the work spindle. The only variation in the setup is the need to counter balance the offset end of the spindle. Dummy material is added opposite the

offset on the same end of the spindle. The balance should be precise to the extent that, when floated on air, the spindle will rest at any position about the axis of rotation.

Spindle Housings - The faces of the spindle housing are lapped parallel to 20 micro-inches, as attested to by scanning the faces with an electronic displacement indicator on a granite surface plate.

Thrust Bearings - Thrust bearings are lapped to the same degree of parallelism as the housing. The Graphitar G-2 face is dry lapped with diamond powders on a flat Meehanite GB lap. The process is identical to that described for the journal-bearing shoe.

The fitup of the thrust bearings is controlled during this lapping procedure. The back thrust shoulder on the cutterhead spindle is compared with the face of the back thrust bearing and, on a granite surface plate, should measure the same height. This comparison is made with the spindle projecting through the housing, resting on the face of the nose of the spindle, and with the front thrust bearing in place engaging the thrust face. Lapping of either the Graphitar G-2 component or the thrust shoulder is performed, whichever is necessary to bring both surfaces into the same plane.

A similar operation is performed on the work spindle, the only difference being that the thrust shoulder should be 0.006 inch less in height than the back thrust face. This difference is the required amount for preloading the flexure in the rear thrust-bearing assembly.

Cutterhead - Lapping and fitting the surfaces of the cutterhead is a somewhat less tedious process. The V surfaces shown in Figure 13, Items 110A and B and Section C - C, are lapped flat and then corrected to yield a true 90-degree angle as attested to by looking into the corner with an autocollimator. A true 90-degree angle will yield a single image; a near 90-degree angle will yield two images. Correction is applied until a single image appears. Under these circumstances, the 90-degree angle will be true to within one second of arc.

The square surfaces shown in Figure 13, Item 109D and Section C - C, are obtained by first lapping opposite sides parallel as attested to by scanning the surfaces with an electronic displacement indicator. One surface is moved over a granite surface plate; the opposite surface is sensed with the indicator stylus. The 90-degree angle is determined by first setting an autocollimator to 90 degrees with reference to a granite surface plate. Then, each angle of the work is checked by having one surface contact the surface plate while the adjacent surface is measured with the autocollimator.

Figure 13. THE CUTTERHEAD.

Fitting of Item 109D to 110A and B, shown in Figure 13, is accomplished by lapping at the joint between the V's. Proper fit is attested to by coating the male mating surfaces with prussian blue and then assembling the components. Movement of the inner piece should meet with several pounds of resistance. When dismantled, the bluing should indicate even contact all over.

The bore shown in Figure 13, Item 109D, is completely finished lapped, and the outside diameter of Item 109A, Figure 13, is lapped to fit the bore. The proper fit is attested to by engaging the two components and noting that movement meets with a resistance of several pounds.

The differential threads are lapped by engaging the nut, Figure 13, Item 109B, with Items 109A and D until a smooth action is noted.

All of the lapping on the cutterhead components is done with Size 9, 6, and 3 diamond powders suspended in olive oil.

ASSEMBLY AND ALIGNMENT

Work and Cutterhead Spindle Assemblies

Assembly of the work and cutterhead spindle components is conveniently done on a surface plate because of the need for using instruments such as an autocollimator or an electronic displacement indicator during the procedure.

To assemble the work spindle, the housing shown in Figure 4, Item 101A, is first mounted on two-inch-thick parallels, followed by the insertion of the spherical-seat adjustments, Items 103A and B. Next, the journal-housing shoe clusters are inserted in each end of the housing. It is to be noted that one of the three shoes has a spherical seat located at the top of the housing; the other two shoes are connected to the master shoe through the flexures shown in Figure 4, Item 104C. No flexure is required between shoes at the bottom of the housing. At this position, a thin wedge is applied between the shoes to expand them so that the shoe cluster presents an inside diameter about $1/32$ inch larger than the journal diameter.

A piece of $2\frac{1}{2}$ -inch-diameter aluminum tubing, 24 inches long, is counter bored to fit the $2\frac{1}{4}$ and 2-inch diameter on the pulley end of the shaft. This tubing is fitted to the shaft, the front thrust bearing is placed over the shaft in its approximate position, and the combination is threaded through the housing. At an axial position where there is about one inch of space between the back of the thrust bearing and the housing, the shaft is momentarily left to rest on V blocks which have been provided for this purpose. With needle-nose pliers, the wedge between the shoes is removed. The spherical seat adjustments are then hand tightened until they are felt

to bear on the shoes. Next, air at 50 psi is supplied to the shoes through a flexible hose. After removal of the V blocks and the aluminum tubing, the shaft will float. The shaft is axially positioned against the front thrust bearing and the air supply turned off. Cap screws are applied to secure the front thrust bearing to the housing. The outside edges of the bearing should be flush with the surfaces of the housing. The rear thrust bearing is secured in a similar manner.

With the edges of the thrust bearing as a reference, the shaft is centered to a tolerance of 0.001 inch by manipulating the spherical-seat shoe adjustment. The rotating component of the thrust bearing (Figure 4, Item 102A) is secured with the thrust nut (Figure 4, Item 103C). The air supply is connected to the thrust bearing through a rubber hose. The spindle assembly is now ready for precision alignment.

An autocollimator is set up opposite to the plane surface of the spindle nose and the reference setting made. Air at 100 psig is turned on and the shift in the image is observed. If the centerline of the spindle is aligned at right angles to the thrust face, there will be no shift. If there is misalignment, however, an angular change will be observed by a shift in the image position. Noting the direction of the shift, it is possible to determine the direction of misalignment. Adjustments to the spherical seats are made in increments of 0.001 inch. When a position is reached where there is no shift in the image, the alignment of the journal bearings with respect to the thrust bearing is accomplished.

The next procedure requires setting of the proper clearance in the journal bearings. Air pressure is set at 50 psig and the spherical seat adjustments are manipulated so that the spindle is just free to rotate; ie, the slightest bit of tightening will cause the shoes to freeze on the spindle. The latter procedure may cause slight angular misalignment in the thrust bearing, making it necessary to repeat the first alignment procedure and the bearing-clearance adjustment. A state will be reached, however, where the angular alignment and the proper bearing clearance exist simultaneously.

The same assembly and alignment process is used to bring the cutterhead spindle into proper adjustment, the only difference being the addition of a counter weight to the offset end of the spindle to eliminate unbalance.

Spindle Assemblies and Base Casting

The final assembly and alignment procedures are concerned with mounting the spindles on the machine-tool base casting and aligning the spindles with the base casting and with each other.

The base casting shown in Figure 1 is first set in place and leveled from the top machined surface. The work-spindle assembly is then secured to the base. An auxiliary arm extending about six inches from the periphery of the nose of the spindle is secured to the plane surface. A 0.0001-inch dial indicator is attached to the end of the arm so that it can scan the top machined surface of the base casting. Air is then supplied to the work spindle and the top surface of the casting is scanned, noting the readings on the indicator. The spindle is adjusted to read zero and the anchor bolts are firmly tightened.

Dynamic balancing of the work spindle is accomplished by modification of one of the gaging interferometers. The incandescent white-light source is removed and replaced with a stroboscopic source that can be precisely synchronized with the rotational frequency of the work spindle. This work was done using a Strobotac, Model 1531-A and a pulse delay unit, Model 1531-PZ, with a photoelectric pickup.

Light is admitted to the interferometer through an externally mounted condensing lens that focuses an image of the source through a right-angle prism into the instrument. The timing mark for the photoelectric pickup unit is placed on the drive pulley of the work spindle by first placing a piece of dull-black adhesive tape, 1/2 inch wide, around the pulley periphery. A piece of white adhesive tape, 1/8 inch wide by 1/2 inch long, with the long dimension axially oriented, is placed over the black tape. The black-adhesive-tape background is necessary for precise triggering of the Strobotac. Any appreciable amount of light reflecting from the background constitutes "noise" in the system and makes synchronization erratic. A narrow, flat drive belt must be used to leave the timing mark exposed to the photoelectric pickup.

Referring to Figure 10, clamps (not shown) holding the mounting bracket are loosened and the measuring system is lowered to a position where the gaging interferometers are opposite the periphery of the work spindle. Next, the Strobotac light system is arranged for proper illumination. The periphery of the spindle nose is marked off in 45-degree spacings and numbered from 0 degree. A reference mark is placed on the adjacent stationary surface of the spindle assembly. With the use of auxiliary mirrors, stray light from the Strobotac will illuminate these markings.

The spindle is rotated at 2,000 rpm and the position adjustment of the interferometer is manipulated until the zero-order fringe appears in the field, coincident to a reference in the interferometer eyepiece. A micrometer eyepiece with a scale of 0 to 100 is used. In the polar-coordinate plot shown in Figure 14, the radial dimensions represent the values read from the micrometer eyepiece. In this instance, each unit represents a radial displacement of the spindle of two microinches.

Static and dynamic plots are necessary to determine the geometrical dynamic behavior of the spindle. The static plot represents out of roundness of the periphery of the spindle nose. The lack of true roundness is of no consequence insofar as the

Figure 14. DYNAMIC BALANCE OF THE WORK SPINDLE. (Balance not Achieved)

accuracy of rotation is concerned. A plot of this surface, however, serves as a reference for the determination of the dynamic performance.

The time-delay adjustment is manipulated until 0 degree appears at the reference mark on the spindle housing; the position adjustment of the interferometer is manipulated until the zero-order fringe is coincident to "30" on the micrometer scale. Then, the time delay of the Strobotac is adjusted to make the 45-degree mark on the periphery of the spindle nose coincident with the reference mark on the housing; the zero-order fringe position is noted from the interferometer. This procedure is repeated for each angular position of the spindle until 360 degrees have been scanned.

A plot of these readings is made and compared with the static plot. If the spindle is in perfect dynamic balance, the static and dynamic plots will be superimposed.

Eight equally spaced tapped holes were designed in the periphery of the spindle nose for the application of slugs for balancing purposes. A slug is added to the minus side of the spindle, and the balancing procedure is repeated until the dynamic and static plots are superimposed. Figure 15 shows the last of several plots indicating that the dynamic balance had been satisfactorily achieved.

Figure 15. DYNAMIC BALANCE OF THE WORK SPINDLE. (Balance Achieved)

A similar balancing procedure is performed at the pulley end of the work spindle. Instead of looking at the rotating element with the interferometer, however, a 1/4-inch-square mirror is cemented to the side of the spindle housing and the interferometer is mounted to look into the mirror. Dynamic unbalance will cause vibrations which can be sensed by the interferometer. Consequently, a polar coordinate plot is made with reference to the origin of the x and y axes. If there is no vibration, a perfect circle will be plotted; otherwise, an oval or irregular plot will result. By trial and error, a balance can be achieved where a near-perfect circle is plotted. Balancing slugs are applied to radially tapped holes in the drive pulley.

After aligning and balancing the work spindle, the cutterhead spindle is put in place and its anchor bolts tightened. Next, an autocollimator is mounted externally to look into the corner mirror formed by the lapped plane surfaces on the nose of each spindle. If the spindles are oriented 90 degrees to each other, a single autocollimator image will appear. If, however, the spindles are out of position, two images will appear. If this is the case, shimming is applied beneath the housing of the cutterhead spindle until a single image is achieved in the autocollimator.

The next step is the alignment of the cutterhead spindle to the base casting. A lapped surface exists on the offset portion of the cutterhead spindle that is made normal to the spindle axis. The cutterhead spindle is swung to one side and a depth micrometer measures the distance from the lapped surface to the vertically machined surface on the base casting. The offset portion is swung about 200 degrees to the opposite side and again the distance is measured from the lapped surface to the vertically machined surface. The cutterhead spindle is adjusted angularly in a horizontal plane until these readings are the same to within 0.001 inch.

An external mount is provided for the autocollimator to look into the plane lapped surface on the nose of the cutterhead spindle; a zero reference is noted and held for further use. Then the spindle is positioned so that the centerline of the cutter feed mechanism is coincident with the axis of the work spindle in a front-to-back sense. Figure 16 shows a dimension of 0.096 inch between the lapped plane surface on the nose of the cutterhead spindle and the periphery of the work spindle. This dimension was arrived at by the summation of measurements of the associated components. The cutterhead spindle is shifted from front to back until the 0.096-inch clearance is obtained and, at the same time, the autocollimator image is retained at zero.

Centering the cutterhead spindle so that its axis of rotation intersects the axis of rotation of the work spindle is accomplished by first mounting an aluminum test piece on the work spindle and taking a preliminary cut over the surface with a diamond knife, providing a highly reflective surface that may be used for centering with the aid of an interferometer mounted on the cutterhead.

Figure 16. ALIGNMENT OF THE WORK SPINDLE TO THE CUTTER-HEAD SPINDLE.

The cutterhead spindle is rotated so that the axis of the cutterhead is in a horizontal plane. The interferometer, looking at the surface of the test piece, is adjusted so that the zero-order fringe is coincident with the reference in the eyepiece. Both the work spindle and the cutterhead spindle are rotated 180 degrees. An observation is again made with the interferometer. If the axes of both spindles intersect, the zero-order fringe will be coincident with the reference in the eyepiece. If not, adjustment is made until the fringe is observed in both positions. When the zero-order fringe appears in two positions 180 degrees apart, when the autocollimator image is at zero, and when a 0.096-inch clearance exists between the plane surface on the nose of the cutterhead spindle and the periphery of the nose of the work spindle, the cutterhead spindle is properly set.

Interferometer Measuring System

The interferometer measuring system must be aligned so that an accurate comparison of a gage-block length to a hemisphere diameter is assured. This final alignment is accomplished with a finished hemisphere in place and the measuring system in its operating position.

A gage block, or gage-block combination, is selected that is approximately equal to the diameter of the hemisphere. A reference right-angle block accurate to one second is set with one face contacting the plane surface of the work-spindle nose;

the other surface is set at a right angle to the centerline of the gaging interferometer and facing the left-hand interferometer. This interferometer is adjusted to produce the typical circular fringe pattern. By adjusting the reference surface, the fringe pattern is centered on the horizontal cross hair in the interferometer eyepiece. The interferometer carriage is moved to the rear, facing the gage block. The position adjustment of the interferometer is manipulated to produce interference fringes from the gage-block surface. Then the gage block is adjusted angularly about the cutter-head spindle centerline until the fringe pattern is centered over the horizontal cross hair.

By means of the traverse adjustment, the interferometer is made to scan the gage-block surface. By noting the drift of fringes across the field, it is possible to determine the direction of angular misalignment of the gage block about the axis of the work spindle.

Angular adjustment of the gage block is made until there is essentially no drift of fringes across the field as the interferometer scans the gage-block surface. Then the reference surface of the interferometer is further adjusted to bring the concentric fringes coincident to the vertical cross hair, being careful to retain coincidence with the horizontal cross hair.

The interferometer carriage is moved back to "look" at the hemisphere. With the traverse adjustment, the interferometer carriage is positioned until the fringe pattern is coincident with the vertical cross hair. If the interferometer is at the proper height, the fringe pattern will also be coincident with the horizontal cross hair. The clamp on the mounting bracket is loosened, and the whole measuring system is raised or lowered until coincidence is attained. The clamp is then tightened.

At this time, concentric fringes coincident to the vertical and horizontal cross hairs may be observed whether looking at the hemisphere or the gage block. Having attained these conditions, the left-hand interferometer is completely aligned.

The right-hand interferometer is positioned to face the other end of the gage block, and the reference surface of the interferometer is adjusted until the concentric fringe pattern is coincident with both the vertical and horizontal cross hairs. Then the interferometer carriage is moved to a position where the left-hand interferometer is opposite the hemisphere and is positioned by the traverse adjustment for complete coincidence of the fringe pattern to the cross hairs. The right-hand interferometer at this time is completely aligned angularly and only needs to be put into its proper position.

By observation of the concentric fringe pattern, the direction required for proper alignment can be determined. By shimming, the interferometer can be raised or lowered to bring the fringes into coincidence with the horizontal cross hair. A magnetic mirror, attached to the external framework of the interferometer, is

viewed by an externally mounted autocollimator to retain its angular alignment while the shimming operation is being effected.

After carrying out these procedures, complete coincidence of the fringe patterns with the cross hairs in both interferometers should be observed, either looking at the gage block or at the spherical surface.

PERFORMANCE EVALUATIONS

ENVIRONMENTAL CONDITIONS

The performance of a machine tool capable of operating in microinch ranges can be greatly affected by the environmental conditions. Any efforts at accurate performance evaluation can be completely frustrated by a lack of environmental control. Perhaps the two factors of greatest consequence in this respect are temperature and vibration.

The laboratory area in which most of the work on the hemisphere turning machine was performed and in which performance valuations were made was maintained at a temperature differential of $\pm 0.2^{\circ}$ C around the machine. However, with the activity of two people around the machine, temperatures would sometimes vary as much as 0.5° C.

Vibration control was maintained by the inherent design of the work room. The floor of the laboratory area was isolated from the surrounding building. It can be thought of as an island of concrete three to four feet thick on three feet of sand and three feet of gravel. The periphery of this area was isolated from the building by six inches of cork. The net effect of this structure was the attenuation of external disturbances by a factor of 20 to 40. The normal vibration level in the center of the room was measured as one microinch peak to peak.

EVALUATION TESTING

Rotational and Thrust Accuracy

The rotational accuracy of the work spindle was evaluated under both static and dynamic conditions. The static check was made by contacting a 2.500-inch boring gage to the plane surface of the spindle nose and indicating the bore with an electronic displacement indicator having a sensitivity of two microinches. The bore of the ring gage had been checked on a bore interferometer and its departure from roundness had been evaluated as less than two microinches. The results of this check showed a rotational deviation in the work spindle of approximately two

microinches—the accuracy limit of the checking system. It is conceivable that the spindle's rotation was more accurate than the indicated figure.

The thrust accuracy of the work spindle was checked by wringing a gage block over the center of the plane surface and observing the fringe displacement at the center with the interferometer mounted in the cutterhead. The observed deviation was two to three microinches.

Rotational and thrust accuracies were checked for the cutterhead spindle. Approximately the same order of deviations noted in the work spindle were observed.

Dynamic Balance

The dynamic balance of the work spindle without work showed about a two-microinch deviation at 2,000 rpm. When work was mounted, however, the deviation increased to five microinches. By adding balancing slugs to the periphery of the nose of the spindle, this value was reduced to two microinches.

Temperature Drift

Temperature drift of the work spindle was checked for both radial and axial change while rotating at 2,000 rpm. It was noted that after an hour or two of running, the cutterhead spindle was no longer centered with respect to the work spindle by a difference of about ten microinches. During this time, temperature changes were noted in the base casting. Consequently, there is some doubt as to whether or not the difference occurred because of temperature changes in the base casting or because some radial drift did actually occur in the spindle. Additional work will be necessary to establish definite conclusions.

Axial-position change was noted to vary 84 microinches after a running time of three hours at 2,000 rpm. A plot of this change is presented in Figure 17. During this time, the spindle-nose temperature rose 2.38°F over the room temperature. The observed axial growth was 84 microinches. Of this amount, approximately 24 microinches occurred in the spindle nose leaving 60 microinches growth for the shaft, observed in the upper part of the spindle. Since the bearing design of the spindle is symmetrical about its midpoint, it is reasonable to assume that a growth of 60 microinches also occurred in the lower part. If this is true, then the total growth of the shaft is 120 microinches. This value would represent an average temperature rise of about 1.1°F in the spindle shaft.

Speed Drift

Both axial and radial drift of the work spindle were checked with respect to rotational speed over a range from 0 to 2,000 rpm. The spindle nose, under Strobotac-lamp illumination, was observed with interferometers. These changes were noted to be essentially zero.

Figure 17. CHANGE IN GAS-FILM THICKNESS AS A FUNCTION OF THE RUNNING TIME. (Upper Thrust Bearing on the Work Spindle)

Deflection

Static deflection tests were run for both the work and cutterhead spindles. The results were practically identical. Axial deflection was measured to be $0.5 \mu\text{in/lb}$ and radial deflection, $2 \mu\text{in/lb}$. The deflections were sensed with an electronic displacement indicator; the forces were applied with a spring balance over a range of 0 to 20 pounds.

Comparing these results with the predicted design deflections, as summarized in Table 1, it may be noted that the radial deflections fall between the predicted maximum and minimum for both spindles. The axial deflection of $0.5 \mu\text{in/lb}$, although still quite small, was considerably more than the predicted deflection of less than 25 angstrom units. This loss of thrust stiffness, which is traceable to the relatively high porosity of the Graphitar G-2 used in the thrust bearings, is discussed in the paragraphs that follow.

Figure 18 shows a curve indicating the gas-film thickness with the average pressure in the film. The data were developed from the upper thrust bearing of the work spindle, which is typical of all the thrust bearings. The operating film thickness is approximately 225 microinches. From Figure 18 it may be noted that the slope of the curve at this point is about 5, using the indicated units. Comparing this curve

Figure 18. GAS-FILM THICKNESS AS A FUNCTION OF THE AVERAGE UNIT PRESSURE IN THE FILM. (Upper Thrust Bearing on the Work Spindle; Nitrogen Supply at 100 psig)

with the 200-psig curve shown in Figure 2, it may be noted that the slope of the 200-psig curve is about 2.5 units.

The significance of these slopes is that they represent the degree of stiffness in the bearing. The smaller the slope, the stiffer the bearing. The equipment designed for this project was based on the 200-psig curve of Figure 2. Several air-bearing designs were developed previous to the present work, and little variation in the Graphitar G-2 porosity had been noted, at most 20 percent. The Graphitar G-2 used in the thrust bearings for the hemisphere turning machine, however, showed excess porosity, as indicated by comparing the curves in Figures 19 and 20.

From the 200-psig curve of Figure 19 (the experimental curve on which the equipment design was based), the predicted gas consumption for a 225-microinch-thick film was 0.0104 scfm/in². Comparing this value with the curves in Figure 20 (the actual gas consumption of the upper thrust bearing of the work spindle at 100 psig and with a 225-microinch-thick gas film) it is noted that about 0.041 scfm/in² is required, or about four times more gas at half the pressure. In fact, the porosity of the Graphitar G-2 was so great that it was impossible to develop the required flow to produce 200 psig with the existing supply equipment. The equipment is, therefore, operated at 100 psig with an overall gas consumption of about twice that predicted. Gas-film stiffness is reduced by a factor of two.

Figure 19. GAS CONSUMPTION AS A FUNCTION OF THE FILM THICKNESS. (2" x 4" Flat Experimental Air Shoe - Graphitar G-2; Nitrogen Gas Supply)

Figure 20. GAS CONSUMPTION AS A FUNCTION OF THE FILM THICKNESS.

Measuring Accuracy

Diameter Measurements - Diameter measurements refer to those taken at the equator of the hemisphere. Trial measurements were made using the interferometer system on an oversized hemisphere of 4.062500 inches. One hemisphere diameter that was turned was measured several times to be 4.062526 to 4.062530 inches with reference to a specific gage-block combination. The measuring operations took place at temperatures varying between 20.35 and 19.9° C. The final diameter measurement was arrived at by compensating for the temperature difference between the actual temperature and standard temperature, which is 20° C (68° F).

Sphericity Measurements - Sphericity measurements were taken with the interferometer mounted in the cutterhead spindle with reference to the axis of rotation of both the cutterhead spindle and work spindle. The total deviation of both spindles from true rotation was less than 2.5 microinches.

One hemisphere turned with a carbide tool was measured with a total deviation from sphericity of less than 8 microinches. The center of sphericity was established by positioning the cutterhead spindle interferometer to read zero at two points on the equator 180 degrees apart and at the pole. Although the actual measurements show a deviation of eight microinches, it is possible that the true deviation is greater. If the inaccuracies of the spindles fall so that one spindle is at a maximum in one direction and the other a maximum in the opposite direction, then the true deviation from sphericity would be 13 microinches. For the cutting done with the diamond knife, however, it appears that the accuracy of machining is essentially equal to the deviations of the spindles. If this is true, final machining of a hemisphere should be true within ± 2.5 microinches, or a total deviation of 5 microinches.

HEMISPHERE TURNING PROCEDURES

MACHINING

Before a test hemisphere (see Figure 21) is finished on the hemisphere turning machine, it is first machined by conventional techniques until 1/32 inch of material (measured on the diameter) is left on the spherical surface. The diameter face is then lapped true on a cast-iron lap using Size 9 diamond powder suspended in olive oil. Next, the test piece is mounted on the hemisphere turning machine with eight Size 10-24 cap screws, finger tightened. Then, using an electronic displacement indicator, the test piece is made to run true with the work spindle to 200 microinches. Once trued, the cap screws are tightened using approximately six inch pounds of torque.

Note: $\frac{32}{\sqrt{}}$ finish all over except where otherwise noted; material: Type 2014 aluminum alloy forging.

Figure 21. TEST HEMISPHERE.

A conventionally sharpened tungsten carbide cutting tool is used for the initial turning at a work-spindle speed of 2,000 rpm, with a tool advancement rate of about 0.001 inch/revolution, and a depth of cut of 0.01 inch. The final cut sizes the hemisphere to 0.001 inch over the finish size:

The rough turning tool is replaced with a tungsten carbide chisel. (The included angle of the chisel is 75 degrees of arc and it is oriented to the spherical surface so that the clearance angle is 7 1/2 degrees and the straight-line cutting edge is tangent to the surface.) This tool is first sharpened by conventional diamond grinding, then lapped on cast iron with Sizes 6, 3, and 1 diamond powders suspended in olive oil. Inspection of this lapped edge is done under a 40 - 100X microscope with the edge of the chisel oriented toward the observer. Direct white-light illumination is used. Lapping will produce a cutting edge that cannot be seen by this method of viewing, except for some portions that are seen as diffracted light. This condition will represent the limit of sharpening.

The hemisphere cutting operation with the mounted chisel consists of cuts about 0.0001 inch deep, again with a tool-advance rate of 0.001 inch/revolution. A

spindle speed of 2,000 rpm keeps welding at the cutting edge at a minimum. Welding is also reduced by completely covering the work surface with a very light coat of olive oil applied with a chamois.

Finally, the tungsten carbide tool is replaced with a diamond knife sharpened to the same general geometry as the chisel. The work-spindle speed, the rate of advance of the tool, and the use of olive oil applications to reduce welding are the same as in the previous operation. Two to four passes are made over the surface with a depth of cut of about 40 microinches. The final pass should have a 5 to 10-microinch depth cut.

Caution must be exercised near the finish of the machining operation to prevent undersizing the work as a result of thermal expansion of the hemisphere during turning. It is necessary to know temperature conditions within an accuracy of about 0.1°F to measure diameters to an accuracy of 5 microinches with respect to a gage block. The work (Type 2014 aluminum) has a thermal expansion coefficient of $12.4 \times 10^{-6}/^{\circ}\text{F/in}$, while the steel gage block has a coefficient of $6 \times 10^{-6}/^{\circ}\text{F/in}$. Thus, for example, a 1°F error in temperature measurement will produce a 26-microinch error in the diameter measurements of a 4-inch hemisphere. Waiting periods are therefore necessary to allow the work to come to a uniform temperature. Temperature measurements are taken with thermocouples inserted in wells provided in the hemisphere, as shown in Figure 21.

MEASURING

Figure 10 shows the measuring system used to determine the diametric accuracy and sphericity of the hemisphere during the finishing operation. This system is used when the hemisphere is to within approximately 0.0005 inch of the finished size.

To determine the diameter of the hemisphere, a gage block or gage-block combination, representative of the size of the sphere, is mounted on the gage-block support (not shown) so that its midpoint is approximately on the centerline of the cutterhead spindle. The interferometer carriage is moved back to a position where each of the gaging interferometers "look" at an end of the gage block. The differential screw adjustment is set in its mid position. While viewing through the interferometer eyepiece, the position adjustment of the left-hand interferometer is manipulated until the zero-order fringe, black in appearance, appears in the field.

The mounting for the gage block permits angular motion about all three axes. Angular adjustment of the gage block is made until the center of the fringe system is coincident with the cross hairs in the eyepiece. Then, the position adjustment is

again manipulated until the zero-order fringe becomes the center of the fringe system. (The zero-order fringe will appear as a black dot whose center coincides with the intersection of the cross hairs.) The operator then moves to the right-hand interferometer and manipulates the position adjustment until the zero-order fringe also appears as a dot. Since the interferometer system is already set up, the zero-order fringe dot will automatically coincide with the cross hairs. Both interferometers are now properly set to represent the gage-block length within an accuracy of one to two microinches.

Using the traverse adjustment, the interferometers are next positioned so that their centerlines are approximately coincident with a diameter of the hemisphere. By manipulation of the traverse adjustment and the differential screw for positioning the undercarriage, the zero-order fringe is again made to appear in the left-hand interferometer as a dot coincident with the cross hairs. If the diameter of the hemisphere is exactly equal to the dimension of the gage block, a zero-order fringe will appear in the right-hand interferometer as a dot. But, if the hemisphere diameter is larger (say by 26 microinches), then the zero-order fringe will appear as the second circular fringe from the center. In this case, a red dot will coincide with the cross hairs.

Red, with an approximate wavelength of 25.75 microinches, is used as a reference. If interference occurs every $1/2$ wavelength, a second red fringe will represent a difference of approximately 26 microinches.

Comparison of hemisphere diameters smaller than the gage-block dimension (say 26 microinches smaller) cannot be conveniently made because the zero-order fringe will be absent in the right-hand interferometer, thereby losing the reference. To overcome this deficiency, the interferometers can be set with reference to the gage blocks in such a way that the zero-order fringe represents a smaller dimension. This adjustment is accomplished by positioning the interferometers opposite the reference gage block. This time, however, instead of referencing the black dot, the setting is arbitrarily made on the third red fringe from the zero order. The zero-order fringe therefore appears as the third concentric fringe in the field, and the gage-block length with reference to the zero-order fringe would be the gage-block length less 38.625 microinches. Thus, when the interferometers are positioned for the second time to look at the diameter of the hemisphere, a red dot will appear in the right-hand interferometer, with the black zero-order fringe appearing as the first circular fringe around the dot. Under this system, the size of the work would be equal to gage-block length less three red fringes plus one red fringe, or a total of minus two fringes.

In cases where a fringe does not appear as a precise dot, interpolation can be made accurate to $1/5$ of the fringe spacing. This value amounts to an approximate error of two microinches.

Roundness measurements at the hemisphere's equator can be made by viewing fringes in either gaging interferometer while the hemisphere is rotated on the work spindle. Since the spindle has a rotational accuracy of about two microinches and the sensitivity of the interferometer is about one microinch, roundness measurements can be made to an accuracy of three microinches. Since out of roundness can show up as a variation in diameter, the diameter measurements made as the hemisphere rotates actually constitute a second check on roundness.

Sphericity of the hemisphere is determined through the use of the third interferometer mounted on the cutterhead spindle (see Figure 10). This spindle possesses the same geometrical qualities as the work spindle; ie, its rotational and thrust accuracies will show a total deviation from true conditions no greater than two microinches.

To measure sphericity, the interferometer carriage is moved back to its furthest rear position to allow the cutterhead interferometer to have access to the entire spherical surface. The cutterhead spindle is rotated to place the interferometer at the equator on the hemisphere's left side. The position adjustment is manipulated to produce a zero-order fringe coincident with the cross hairs in the eyepiece of the interferometer. Activating the cutterhead spindle drive, the interferometer scans the surface from the equator to the pole to the equator, 180 degrees from the starting position. Fringe displacement is noted, and a polar plot made from these data. Any number of plots may be made around the hemisphere to determine its sphericity by rotating the hemisphere on the work spindle. These plots, together with the roundness plot made at the equator as a base line, present a comprehensive picture of the geometry of the entire hemisphere.

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PHASE II, SECTION 1

TURNING OF HARD MATERIALS

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INTRODUCTION

The technology developed during Phase I of this program was somewhat limited in scope since it evolved in part from machining processes applied to a soft material of a comparatively sturdy shape.

To broaden this technology, the first part of Phase II (Machining of Hard Materials) was initiated. The purpose of this study was to investigate the effects of work hardness on the machine-tool elements and processes developed in Phase I.

For purposes of comparison, the test-part configuration chosen was a hemisphere practically identical in shape to the hemispheres made during the Phase I study. The materials investigated were sintered tungsten and a commercial grade of Type 304 stainless steel.

Items of particular interest in these studies were: (1) geometrical accuracy, (2) tool wear rate, (3) surface finish, (4) changes in forces acting on the machining systems, (5) temperature control (heat dissipation), (6) apparatus capability operating under adverse conditions, and (7) other critical factors unforeseen in the studies made thus far.

EXPERIMENTAL APPARATUS

The apparatus for this study was the hemisphere turning machine, including its metrology system, with the following significant modifications: (1) cutting-tool configuration, (2) cutting-tool materials, and (3) relative velocity between the cutting tool and the work.

Initially, the same chisel-shaped, straight-cutting-edge tool with an included angle of 75 degrees was used. Such tools are usually mounted with a 6-degree clearance angle, 9-degree positive back rake, and 0-degree side rake. However, when the chisel-shape configuration did not yield satisfactory results, changes in tool application were made to further the investigation. A list of the various kinds and grades of tool materials is shown in the appendix to this section, Exhibit A.

Changes in the work-spindle speed were necessary to produce the desired velocity between the tool and the work. This change was achieved by adding a jack shaft to the hemisphere turning machine between the drive motor and the spindle-drive sheave. Variation in sheave sizes and motor speeds yielded work-spindle speeds from 10 to 300 rpm.

EXPERIMENTAL PROCEDURE

INVESTIGATION OF SINTERED TUNGSTEN

Initial efforts to machine the surface of a sintered tungsten hemisphere, 4 1/2 inches in OD, were very discouraging, because the tool wear rate was excessive. In fact, no commercial tool material had sufficient life to finish a roughing cut, regardless of the cutting speed, tool configuration, or cutting lubricant. Typical cutting speeds ranged from 10 to 30 rpm for normal materials in this hardness range (Rockwell C-40 to C-41).^(k) Cutting-tool clearance angles were maintained at 6 degrees and the side rake at zero degrees, while back rake varied about 20 degrees. At best, any variations in the tool configuration had a minor effect. Finally, all efforts to use conventional tool materials were abandoned.

The diamond knife with its normal configuration produced surprising results. Excessive wear and edge chipping were not observed after many passes were made over portions of the spherical surface. A full cut over the spherical surface could not be made because the surface had been severely distorted by numerous unsuccessful attempts with conventional tool materials.

Various speed ranges were explored, settling for about 140 rpm of the work spindle. Roughing cuts, 0.002 inch deep, were made with the diamond tool with a feed rate of 0.005 inch/revolution of the work spindle until the spherical shape was restored. Finishing cuts were made about 0.0001 inch deep with a tool feed of 0.002 to 0.005 inch/revolution.

Surface examination with a 75X-point interferometer indicated that sintered tungsten was not sufficiently dense to yield a two-microinch rms finish. However, in isolated areas that appeared sufficiently sound, estimates were made of the potential finishing capability of the machining process. Surface irregularities measured approximately 10 microinches peak to valley. Such a surface character would yield about 3.3 microinches rms.

In view of the difficulty of obtaining sound, dense tungsten and the fact that the results obtained were sufficient to establish the feasibility of the principles involved, the investigation of this material was terminated at this point.

(k) Some molybdenum steel alloys in a hardness range of Rockwell C-40 to C-44 are relatively easy to machine with tungsten carbide tool material.

INVESTIGATION OF TYPE AISI 304 STAINLESS STEEL

A Type AISI 304 stainless steel hemispherical test specimen was machined by conventional shop practice to the dimensions shown in Figure 21 (Phase I), thus allowing 0.015 inch of stock to be removed during the experimental machining.

The spherical surface was semifinished with the standard chisel-shaped cutting tool using Kennametal K-11 tool material. Work-spindle speeds varied between 120 and 150 rpm, with depth of cuts varying between 0.001 and 0.0005 inch and feed rates of 0.002 to 0.005 inch/revolution of the work spindle. The results were consistent with general machining practice and were satisfactory for the purpose intended.

Experimental finishing cuts were attempted at 120 rpm with depth of cuts varying between 0.0001 and 0.00005 inch and feed rates between 0.001 and 0.005 inch/revolution. None of the listed tool materials had edge durability to make a complete pass over the spherical surface. Kennametal K-11 and the ceramic tool materials had sufficient durability to cut about three square inches of surface to a finish of three to four rms before severe deterioration became prevalent.

At this time it became obvious that the lack of cutting-edge durability was the greatest deterrent to the machining process. This realization prompted the idea of "continuous edge renewal", a new technique which might satisfy the edge durability and the surface-finish requirements simultaneously, particularly since the surface finish was already demonstrated to be marginal.

Application of the technique is shown in the arrangement at the lower left of Figure 22. The tool (Item 51-H) is about 1 1/2 inches long having a 3/8 inch nominal diameter and a squared machined surface on one end. The tool is lapped to a high-quality finish (less than 1rms) at the diameter and at the plane surface normal to the axis of the cylinder. The intersection of the cylinder and the plane forms the cutting edge. To control the position of the cutting edge, clearance between the cylinder and the bore in the tool mount (Item 51-A) is 10 microinches or less.

The assembly, shown in Figure 22, was designed to mount to the cutterhead of the hemisphere turning machine by attachment to the component labeled Item 109-A, Figure 13. Power to rotate the tool was provided by a 1/50th horsepower gearhead motor assembly with a variable-speed output of 0 to 50 rpm. The output motor shaft was coupled to the input worm shaft through two sheaves, reducing the rotation speed by a factor of 5 to 1. A 1/8-inch-diameter cross-section O ring of suitable length was used as a belt. The gearhead motor was mounted on the horizontal plane surface of Component 110-A, Figure 13.

The following is a typical finishing operation applying "constant edge renewal": Work spindle speed is adjusted to 150 rpm; depth of cut is set to 0.001 inch; tool feed rate is approximately 0.002 inch/revolution of the work spindle; and the speed of rotation of the cutting tool is varied sinusoidally, the objective being to maintain a constant ratio between the tool cutting-edge length and the area of the work machined.

At the pole, the operation required minimum tool rotation. The rotational speed of the tool increased as the tool progressed across the spherical surface, reaching its maximum speed at the equator. Just beyond the equator, the tool had made a complete revolution.

The speed of the drive motor was adjusted by trial and error until a program had been established. At marked angular positions of the cutterhead, the rheostat control for the 1/50th horsepower motor was manually set to its predetermined position, and olive oil was used as a cutting lubricant. A complete turning operation required 10 minutes. Tool resharpening required lapping of the plane surface.

Tool materials of tungsten carbide (Carboloy 330) and ceramic (Carboloy 0-30) were investigated. The ceramic tool performed best.

Although the constant-edge-renewal technique was an improvement over other machining processes, it was not as good as had been expected. The surface finish was only 2 to 3 rms with occasional scratches about 10 to 12 microinches deep. Finish of the surface was improved to 1 - 2 rms by polishing with a wool fabric containing 8,000-mesh diamond dust in olive oil for one to two minutes on the work spindle at 300 rpm. However, the occasional deep scratch was only moderately affected by polishing. This light polishing had a slight effect on the overall geometry. The average depth for material removal was about three microinches.

Microscopic examination of the ceramic tool material offered a possible clue to the source of the occasional deep scratch. The photomicrographs, Figures 23 and 24, show typical areas near the tool cutting edge magnified 2,000X (500X microscopically and 4X photographically). The figures show random dark areas which are considered voids or inclusions of different materials which affect the machining characteristics of the tool.

Another ceramic tool shaped differently and purchased at another time was examined at the same magnification. A comparison of Figure 25 with Figures 23 and 24 shows this material to be either more dense or without structural variation. The studies were terminated at this point.

Figure 22. ROTARY TOOL.

Figure 23. CARBOLOY CERAMIC TOOL. (Stock Size - 0.375" D x 1.5" L, Showing either Voids or Variation in Structure; 500X Microscopically, 4X Photographically)

Figure 24. VASCOLOY-RAMET CERAMIC TOOL. (Stock Size - 0.375" D x 1.5" L, Showing either Voids or Variation in Structure; 500X Microscopically, 4X Photographically)

Figure 25. VASCOLOY-RAMET CERAMIC TOOL. (Stock Size - $5/16'' \times 1/2'' \times 1''$, Showing either Voids or Structural Variation. Note Difference in Voids or Structural Variations Compared to Figures 23 and 24; 500X Microscopically, 4X Photographically)

INTERPRETATION OF RESULTS

TOOL WEAR RATE (See Exhibit B)

No other single factor predominates in the geometrical control of a machining process as does the retention of an exact cutting-tool configuration. Variation in the cutting-tool configuration manifests itself in the form of wear and welding. Of utmost importance in the study of the machining of hard materials is wear; welding, although evident, played a minor roll.

Machining processes are based on precise tracking of a tool cutting edge of optimum configuration. Changes in configuration because of wear introduce factors which defeat the overall objective because:

1. Wear causes a tool edge to work at a constantly varying position. Variance in position constitutes a direct variance in the shape and size of the work. Nothing in the machining process compensates for varying the position of the cutting edge. Furthermore, since the wear rate is inconsistent from tool to tool, it would be difficult to program a system to overcome this disadvantage.
2. As wear progresses, the heat developed in the work increases, causing thermal distortion. Shape distortion is difficult to predict.

3. As the tool configuration is altered through wear, cutting forces increase causing a further change in the tool-edge tracking because of elastic distortion in the structural members of the mechanism.
4. A deterioration in the surface finish is almost always a consequence of tool wear.

After considering all of the consequences of tool wear, no choice exists except a machining process requiring a cutting tool sharper and more durable than any conventional cutting instrument. A novel approach, such as the continuous-edge-renewal process, is required.

Although a direct evaluation of the sintered tungsten test specimen regarding: (1) geometrical accuracy, (2) variations in tool forces, and (3) temperature conditions was not possible, the following deduction may be made: Variation in diamond-tool configuration relative to these three items must have been relatively small, as indicated in Figure 26, otherwise consistent cuts of 0.0001 inch could not have been made. It is reasonable to suppose that sound, dense, sintered tungsten could be machined to conditions nearly as exact as that achieved with the soft aluminum material.

Making the same comparisons in machining Type 304 stainless steel, the results obtained indicated that this material could also be machined to exacting conditions. When this work was terminated, the continuous-edge-renewal technique had demonstrated that:

1. Depth of cuts were controlled to 25 microinches.

Figure 26. DIAMOND KNIFE AFTER MACHINING SINTERED TUNGSTEN.
(Looking from the Work Side; 120X)

2. Temperature rise was 0.8 to 1.4° F. A prediction of the final size could be made within about 18 microinches relative to the temperature effects.
3. Machined spherical surfaces had a maximum deviation from trueness of 15 microinches. This factor indicates that tool configuration is sufficiently constant.

Experiments conducted using hard work materials indicated that the experimental apparatus was sufficiently rugged to withstand adverse conditions comparable to those in normal machine practice. High loads were imposed on the equipment during the application of conventional cutting-tool materials. In some instances, the one horsepower motor stalled; in another, the two-inch-wide taut belt either slipped or ran off the drive sheave. Forces in the order of hundreds of pounds were obviously present. Even though subjected to these conditions, the equipment retained its original accuracy, indicating great ruggedness.

CONCLUSIONS

The results of the investigation indicated that the test parts were machined to an accuracy of 4 microinches/inch with respect to shape and to about the same with respect to size. The fact that a variance as low as that obtained with aluminum could not be achieved can be attributed to the inadequacy of available cutting-tool materials for use with hard materials.

Cutting-tool configurations and durability are critical requirements in the machining processes developed. At present, no ideal tool exists although a near-ideal tool is available for the hard materials investigated, such as the ideal combination of diamond tools for aluminum. The technology would be greatly enhanced by the development of a new tool material which performs on hard materials as does diamond on aluminum.

The hemisphere turning machine is quite rugged and is capable of withstanding tool forces comparable to those encountered in ordinary machining practice.

Temperature control during the machining process is a critical requirement to achieve ultimate accuracy.

EXHIBIT A

MACHINING HARD MATERIALS - CUTTING-TOOL MATERIALS

Cutting-tool materials used in these studies are as follows:

Diamond Knife

White Sapphire

Ceramics

Carboloy 0-30

Vascoloy-Ramet VR-97

High-Speed Tool Steel

Rex 95

Rex 41

Rex 49

Rex 4-V

Cobalt Alloys

Stellite 98M2

Stellite J-Metal

Tungsten Carbide

Kennametal K-7H

Kennametal K-8

Kennametal K-11

Kennametal K-86

Kennametal K-96

Kennametal K-165

Carboloy 883

Carboloy 999

EXHIBIT B

TOOL WEAR RATES

Exhibit A lists the tool materials used in these studies. Performance of the tool materials in a particular class varied little from grade to grade. The maximum wear-rate variation observed was approximately a factor of two. But, from class to class, the wear rates in some instances showed marked differences.

Photomicrographs of the various cutting edges illustrate the more important observations made concerning the tools.⁽¹⁾ Magnification varies from 120X to 500X. In some cases, an edge is shown at one power only, either because of facility limitations or because one power conveys the message. Other edges are illustrated at three magnifications: 120X, 350X, and 500X. In the latter case, the lower powers are required to size the wear land on the tool, thus giving some relative value for the wear rate. The lower power also shows a greater portion of the cutting edge and is, therefore, better for scouting the more interesting features. The 500X magnification is used to observe the fine detail so critical in the evaluation of the machining process. The 350X magnification serves the visual transition from low power to high power; ie, to identify a point on the low-power photomicrograph with the same point at the high power. All photomicrographs, except Figure 26, were magnified 3X or 4X by the photographic process, as indicated.

Wear Rate of Tools Applied to Sintered Tungsten

Figure 28 shows a work-side view of the cutting edge of a white sapphire cutting tool after machining sintered tungsten. Edge deterioration is primarily from chips or cleavages made along the cleavage planes. Apparently, as a result of increasing forces, the strength of the tool material is exceeded, causing relatively gross fractures extending into the body of the tool. A wear land was never observable and it appeared that the tool would break up before a wear land could develop. The material above the cutting edge is welded tungsten. White sapphire has no practical value for turning sintered tungsten.

Figure 29 shows the cutting edge of Rex 4-V high-speed tool steel after machining sintered tungsten. Gross deterioration represents a very rapid wear rate. The conditions of wear represented here are typical of the whole class of steels and cobalt alloys. These materials are useless for machining sintered tungsten.

(1) Figure 27 shows a newly lapped cutting edge typical for all tools prior to the test.

(a) 120X Microscopically, 3X Photographically

(b) 350X Microscopically, 3X Photographically

Figure 27. PHOTOMICROGRAPHS OF THE NEWLY LAPPED CUTTING EDGE ON KENNAMETAL K-7H TOOL.

Figure 28. SAPPHIRE TOOL AFTER MACHINING A SINTERED TUNGSTEN HEMISPHERE. (Note Fractures and Chipped Edge, Looking at the Edge from the Work Side; 500X Microscopically, 3X Photographically)

Figure 29. REX-4V HIGH-SPEED TOOL STEEL AFTER MACHINING SINTERED TUNGSTEN. (Looking from the Work Side; 500X Microscopically, 3X Photographically)

Figure 30 shows three photomicrographs of a tungsten carbide tool after machining sintered tungsten. The wear land is about 0.0024 inch wide by 0.00026 inch deep. The width was determined by measurements taken from the photomicrograph and applying the magnification factor, while the depth was determined by trigonometry. The original face of the tool was set at six degrees to the work surface. Thus, the depth of the wear land is:

$$\text{Depth (d)} = \text{width} \times \sin 6^\circ,$$

$$d = 0.0025" \times 0.105 = 0.00026 \text{ inch.}$$

This value is a measure of the loss of geometry control, and an indication of the relative performance. Wear appears to be the result of attrition. There are no observable fractures or indications of edge deterioration through gross removal of tool material. The individual tungsten carbide particles are resolvable. By normal standards this is a good cutting edge; for the purposes of this study, wear is excessive.

These photomicrographs are typical of all the tungsten carbide tool materials. Wear lands vary in size with the ratio of the largest to the smallest greater than two. These conditions were also typical of the ceramic tool materials.

Figure 26 presents a photomicrograph of the work side edge of the diamond knife after machining sintered tungsten. Slight chipping of the edge can be seen. This edge was applied in a rough machining operation where the depth of cut was 0.002 inch with feeds of 0.005 inch/revolution of the work spindle. Opportunity to apply the diamond knife with the ultimate refinements was not available.

Wear Rate of Tools Applied to Type AISI 304 Stainless Steel

Figure 31 shows photomicrographs of a diamond-knife cutting edge. Figure 31(a) gives a view looking from the work side; Figure 31(b) from the chip side. Gross chipping occurred on both faces. The fractures appear to originate at the cleavage planes of the crystal. Application of diamond knives to Type 304 stainless steel was unsuccessful and further investigation is not necessary.

Figure 28 also depicts the behavior of white sapphire applied to Type 304 stainless steel. Conclusions on this type of cutting tool are those stated earlier (Page 65). This tool material exhibited the same behavior for both experimental work materials.

Figure 32 presents photomicrographs of the work-side edge of a ceramic tool material (Vascoloy-Ramet VR-97) after machining the entire surface of a 4-inch-diameter Type 304 stainless steel hemisphere in a semifinishing operation. The wear land is about 0.001 inch wide by 0.0001 inch deep. In Figure 32(c) the edge appears slightly irregular and clean beyond the edge, indicating no welding. Of all the tool materials, ceramic performed best and was selected, therefore,

(a) 120X Microscopically, 3X Photographically

(b) 350X Microscopically, 3X Photographically

(c) 500X Microscopically, 3X Photographically

Figure 30. KENNAMETAL TOOL K-8 SHOWING WEAR LAND AFTER MACHINING SINTERED TUNGSTEN NEAR THE POLE OF THE HEMISPHERE.
(Total Area of the Machined Surface Equals about 3 in²; Looking at the Cutting Edge from the Work Side)

(a) From the Work Side

(b) From the Chip Side

Figure 31. DIAMOND KNIFE AFTER MACHINING TYPE AISI 304 STAINLESS STEEL LOOKING AT THE EDGE. (120X Microscopically, 3X Photographically)

(a) 120X Microscopically, 3X Photographically

(b) 350X Microscopically, 3X Photographically

(c) 500X Microscopically, 3X Photographically

Figure 32. VASCOLOY-RAMET VR-97 CERAMIC STRAIGHT-EDGE TOOL. (Looking at the Edge from the Work Side after Machining the Entire Surface of a Type 304 Stainless Steel Hemisphere)

as a candidate material for the continuous-edge-renewal experiments. The material performed very well by conventional standards, but the wear rate was excessive for the requirements of this study.

Figure 33 shows three photomicrographs of Stellite 98M2 after rough machining the entire surface of a 4-inch-diameter Type 304 stainless steel hemisphere. The wear land is 0.001 inch wide by 0.0001 inch deep. The bright, irregular line along the edge represents welded material which is more apparent in Figure 33(c). Welding effects were apparent in the surface finish. Edge irregularity was excessive when compared to the wear land. This fact is interpreted as due to excessive cratering on the chip side of the edge. These photomicrographs are representative of the class of tool materials labeled "cobalt alloys" and "high-speed tool steel". The wear lands were larger with the "high-speed tool steels".

Figure 34 shows three photomicrographs of the VR-97 ceramic tool (work-side view) used to machine an entire Type 304 stainless steel hemisphere by the continuous-edge-renewal method. The wear land varies in width from 0.00035 to 0.00018 inch, indicating a depth of wear of 0.000025 to 0.000013 inch. Note the difference in the size of the wear land when compared with Figure 32, and the presence of a void at the cutting edge due to the lack of a completely dense material. The voids are also observable at locations in the body of the tool.

(a) 120X Microscopically 3X Photographically

(b) 350X Microscopically, 3X Photographically

(c) 500X Microscopically, 3X Photographically

Figure 33. STELLITE 98M2 AFTER MACHINING AN ENTIRE TYPE AISI 304 STAINLESS STEEL HEMISPHERE. (Note the 0.001" Wide x 0.0001" Deep Wear Land Looking at the Edge from the Work Side)

(a) 120X Microscopically, 3X Photographically

(b) 350X Microscopically, 3X Photographically

(c) 500X Microscopically, 3X Photographically

Figure 34. PHOTOMICROGRAPHS OF A VASCOLOY-RAMET VR-97 CERAMIC TOOL EDGE AFTER MACHINING TYPE AISI 304 STAINLESS STEEL THROUGH THE APPLICATION OF THE EDGE TO THE WORK BY THE CONTINUOUS-EDGE-RENEWAL METHOD. (View from the Work Side)

PHASE II, SECTION 2

SPHERE TURNING

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OBJECTIVES

The primary objective associated with the sphere-turning studies was the expansion of the technology to include multistage machining processes. This broad objective necessarily included certain secondary objectives, namely:

1. Development of a holding capability where the work is held or fastened to optical-like surfaces without damage to them, without strain, and with a dimensional stability of one microinch per inch of size.
2. Development and practice of metrology concepts to evaluate a precise spherical geometry and to provide a means of relating the geometry of one machining stage to that of another (ie, following removal and replacement of the work-piece) with microinch accuracy.

DESIGN OF EXPERIMENTS

Initial considerations were given to the development of machining-measuring concepts integrated to give maximum geometrical data throughout the machining process. Economy dictated the use of the hemisphere turning machine, with a minimum number of modifications, as the experimental apparatus.

The objective was to determine if a solid aluminum sphere could be machined with a geometry consistent to that obtained with the hemispheres. In dimensional terms, the exterior surfaces of these spheres should not deviate from true spherical geometry by more than $\pm$ five microinches. Surface finish should be better than two microinches rms, and any steps or blends in the finish should be consistent with a two-microinch rms finish requirement.

The capability for machining and measuring hemispheres to an accuracy of $\pm$ five microinches had been demonstrated in Phase I (Page 47).

Integrating two-hemisphere turning operations required the development of the new technology which is described in the sections that follow.

HOLDING

Because the machining process is a two-stage operation, at some point in the machining sequence the sphere must be mounted on optical-like surfaces. Such surfaces are delicate and easily destroyed by conventional holding techniques. The technique developed employs a special wax to join the sphere to a holding

fixture. The wax may be applied and removed from critical surfaces without damage to the surfaces and without strain to the work. The holding method must permit access to the south pole for a metrology purpose. Holding concepts meeting these requirements are shown in Figures 35 through 37.

CENTERING

In concept, two accurate hemispheres must be positioned so that their centers are coincident with one another within 1 or 2 μ in to produce a full sphere. This concept requires a metrology system to locate the center in each hemisphere and a mechanical positioning device which can move a hemisphere so the centers of the two hemispheres coincide.

Two white-light interferometer systems fulfill the metrology requirements. These instruments and their application are discussed in Exhibits A and B; mechanical positioning is achieved by the elevating mechanism discussed in Exhibit C.

Figure 35. ELEVATING MECHANISM.

Figure 37. MEASURING WITH THE POLAR INTERFEROMETER.

EXPERIMENTS

The initial experiments gave insight to new problems which fell into the following categories:

1. Temperature - Would the wax film holding the spherical test piece have a profound temperature effect on the machining process?
2. Strain - Would the wax-holding technique produce stress and strain in the spherical test pieces, thereby causing distortion?
3. Stability - Would the wax be stable enough to withstand a machining process with microinch control?
4. Lubricating Film - Would it be possible to produce a lubricating film with the molten wax so that the spherical surfaces of the test piece and holding fixture were not allowed to contact?

TEMPERATURE

A sphere of Type 2014 aluminum alloy was completely machined in accordance with Exhibit D, except those items involving the polar interferometer. Only minor attention was given to holding an exact four-inch diameter. Two 1/8-inch-diameter holes were drilled at the equator of the sphere 180 degrees apart and one inch deep for thermocouple wells. Two similar holes 180 degrees apart and one inch deep were drilled in the periphery of the holding fixture, as shown in Figure 36. The holes were located so that the wall thickness between the bottom of the hole and the wax film was about 1/16 inch. After making four or five machining cuts over the spherical surface, thermocouples were inserted in the wells and temperatures recorded. Temperature of the sphere rose about 1° F above room temperature; a very small change took place in the holding fixture. These results indicated that the wax acted as a thermal barrier.

STRAIN

A temperature difference greater than 0.1° F between the holding fixture and the sphere was undesirable because strain was induced, and became more severe as the temperature difference increased.

Originally, the plan had been to turn the spherical surfaces and measure the diameter in the fixture, release the sphere from the fixture, and remeasure the diameter. Differences in diameter measurements would indicate the presence of initial strains. However, consideration of possible flow within the wax during the turning operation confused the operation.

The problems of holding without strain were resolved in the hemishell turning machine studies (see Exhibit K, Page 181).

STABILITY

Several times during the initial studies, the diamond-knife machined surface was measured after standing overnight or after standing for two or three days. Always, the surface showed a total indicated runout less than five microinches, and many times less than two microinches. Such consistent results indicate the wax possessed sufficient dimensional stability for the purposes of this study.

LUBRICATING FILM

The final-machining-stage holding fixture was turned to an internal radius of 2.001 ± 0.00005 inches using the cutterhead interferometer system shown on the arrangement of Figure 38. The holding fixture machining operation is discussed in detail

in Exhibit E. One half of a semifinished sphere was machined to 4.000000 ± 0.00005 -inch diameter to test the reliability of the lubricating qualities of the wax film in a molten state. The fixture and the sphere were heated to between 200 and 250° F with an electric heat gun, and wax was applied to the mating surfaces. The fixture and the sphere were joined while the wax was molten, and additional heat was applied to the assembly until a uniform meniscus was observed at the joint. The sphere floated freely on the wax film. After machining the second half of the sphere, the heat gun was used to soften the wax for demounting. Detailed inspection of the spherical surface indicated that physical contact had not occurred. Several spheres were mounted during these experiments, and not one showed evidence of contact.

In subsequent work, measurements were made to determine film thickness. If the initial application of wax was excessive, and if the 3 3/4-pound sphere was allowed to rest on the fixture with only gravity acting on it, the inherent film thickness would be approximately 0.009 inch in thickness.

TURNING OF SPHERES

Several spheres were machined in accordance with the machining procedures for spheres, Exhibit D. From sphere to sphere, there were 15-microinch inconsistencies in the shape and size. It was concluded, therefore, that this inconsistency was the result of the holding technique.

Two spheres, shown in Figures 39 and 40, were to qualify the results of the experiments. Two diameter measurements are shown related to the poles and two to the equator. The graphic representation is the relative shape when freed from the holding fixtures.

In Figure 39, the diameters are 4.000017 inches measured at the poles and 4.000012 inches measured at the equator while held in the fixture by the wax. The step between the two machined surfaces is two microinches at the minimum point and five microinches at the maximum. These measurements fall within the initial goal agreed upon; ie, a spherical surface deviating from a true sphere no greater than $\pm$ five microinches. The five-microinch step is consistent with a two rms finish because peak-to-valley surface deviation may be three times greater than the rms value. The overall surface finish is less than one microinch rms. When the sphere was released from the fixture, the polar diameter measured 3.999990 inches; the equatorial diameter measured 4.000023 inches. Obviously, the sphere had been held under strain during the finishing cut.

In Figure 40, a similar measuring procedure for Sphere 2 is shown. The polar diameter increased to 4.000020 inches and the equatorial diameter measured 3.999996

Figure 39. GRAPHIC REPRESENTATION OF SPHERICITY AND SIZE
- COMPLETELY FREE. (Sphere 4)

Figure 40. GRAPHIC REPRESENTATION OF SPHERICITY AND SIZE
- COMPLETELY FREE. (Sphere 2)

inches. The step between the two machined surfaces is three microinches and the surface finish less than one microinch rms. This sphere met the intended goal either when held in the fixture with wax or when free.

Some confusion results when comparing the measurements of the two spheres. In Figure 39, it is assumed the sphere was compressed under stress while held in the fixture; when released from the fixture, the compressive stress was relieved. Thus, the sphere became larger at the equator and thinner at the poles. But, when looking at the measurements of Figure 40, it is difficult to imagine a situation that would account for the data.

In Exhibit K of Phase II, Section 3 (Page 181), conditions for mounting hemishells in wax provides more favorable temperature control during the hardening of the wax. Figures 62 and 63 (Page 135), show that the geometry of the relatively delicate hemishell is superior to that of the sphere. This fact implies that the technique used for hemishells would eliminate the discrepancies encountered in spheres.

AXIAL STABILITY OF THE WORK SPINDLE RELATIVE TO THE TEMPERATURE

Throughout the sphere-turning studies, axial stability of the work spindle was a problem. Turning operations had to be delayed for three hours after starting the spindle to establish the temperature equilibrium. Stopping the spindle upset this equilibrium and additional time was required to reestablish proper temperature stability. Minor environmental conditions also caused loss of temperature control. For example, an additional person in the room was reflected in the geometry of the sphere.

These disadvantages were eliminated in the hemishell turning machine with the application of a temperature-controlling system which is discussed in Exhibit A of that section (Page 141).

CONCLUSIONS

1. With the machining techniques used during this study two spheres were machined to an accuracy of approximately four microinches per inch.
2. The test parts having delicate, optical-like surfaces were mounted and held without damage to the surface. Wax was used to effect their mountings and acted as a thermal barrier between the work and holding fixture. This barrier had a profound effect on heat dissipation which adversely affected the ultimate accuracy of the system. A mounting material possessing relatively good heat conductivity is highly desirable to attain the maximum in accuracy.

3. Heat, developed by the machining process, is a primary contributor to the loss of dimensional control. Heat, from any source, must be minimized and dissipated to avoid temperature gradients.
4. Residual strains, originating from the holding technique, are relatively small when compared to conventional methods; however, improvement is needed. The need for this improvement is further defined in the section of this report covering the mounting and machining of hemishells (Phase II, Section 3).

EXHIBIT A

POLAR INTERFEROMETER SYSTEM

Introduction

Machining studies of spheres required additional measuring facilities to provide sufficient data to determine sphericity. Consequently, the polar interferometer system was developed. Drawing MR-103, Figure 41, shows that the position-sensing structure (Item 1024-A) is relatively slender compared to the point interferometer. This slender structure, a critical requirement, provides access for diameter measurements over the poles.

Since previous interferometers (including the light source) were bulky, a new slender structure was required. To economize on space, the light source was moved from its conventional location and a smaller beam splitter (3/16" cube) was built. (Up to this time, all cube prism beam splitters were 1/2" cubes.) Details of the interferometer are discussed under Exhibit F.

Measurement Concepts of the System

The polar interferometer system is like the hemisphere measuring system described in Phase I in that the measuring and aligning concepts are similar. The hemisphere measuring system is described under Phase I (Interferometer Measuring System, Pages 40 to 42 and Measuring, Pages 49 to 51). An isometric drawing is also presented under Phase I (Figure 10, Page 28). Figure 10 and Figures 41 and 42 compare the operation of the two systems.

In either system, the diameter of a spherical surface is compared with the length of gage blocks. In Figure 10, the diameter being measured is the one coincident with the centerline of the gaging interferometers; in Figure 41, the diameter is coincident with the centerline of the cube prism beam splitters.^(m) The method of setting the gage length in the polar interferometer system is represented in Figure 42. Both systems require a means of engaging and disengaging the work. The transport mechanism labeled by such items as "undercarriage" and "mounting bracket" in Figure 10, is common to both systems.

(m) See Figure 41, Note 1.

The following procedure describes the operation of the two systems:⁽ⁿ⁾

1. Setting to the gage block:

Hemisphere Measuring - Move the interferometer carriage to the rear opposite the gage block and adjust the position in each interferometer to produce the zero-order fringe coincident with the cross hairs.

Polar Interferometer - Move the carriage to the rear. Swing the gage block into view using the hand wheel (Detail 1021-F, Figure 42). Manipulate the hand wheel (labeled PIC-BG-9—one for each interferometer) to produce the zero-order fringe coincident with the cross hairs in each instrument.

2. Comparing the diameter to the gage block:

Hemisphere Measuring - Move the carriage forward until the interferometers intercept the diameter. Adjust the differential screw of the undercarriage until "bull's-eye" fringes appear in the system. Oscillate between the "traverse" adjustment and the "differential-screw" adjustment until one of the interferometers produces the zero-order fringe (a black dot coincident with the cross hairs). The difference between the gage length of the blocks and the diameter is read in the other interferometer by its fringe color and number of fringes (usually red which equals 12.3 μ in per fringe).

Polar Interferometer - Move the carriage forward to intercept the diameter. With the differential screw (Item 1024-H, Figure 41), manipulate the device until bull's-eye fringes appear in one of the interferometers. Oscillate between the differential screw adjustment and the traverse adjustment (shown in Figure 10, Page 28) until one of the interferometers produces zero-order fringe (a black dot coincident with the cross hairs). The difference between the gage-block length and the diameter is read in the other interferometer by its fringe color. Details of fringe reading are included under Measuring, Page 49.

Optical Alignment of the System

Before starting the alignment procedures for the system, the interferometer must be optically aligned, as discussed in Exhibit F. The following procedure requires the

(n) The two systems will be designated as: Hemisphere Measuring which was included in Phase I and Polar Interferometer which is the system described in this section.

Figure 41. POLAR INTERFEROMETER SYSTEM OF THE SPHERE TURNING MACHINE.

use of a fully machined sphere mounted on the sphere turning machine. Although near perfection is not required, the sphere should consist of two separate hemispherical surfaces (two-stage machining process) with centers lying on the polar axis. This requirement is achieved when the cutterhead interferometer shows that the surfaces intersect within a few microinches. The gage block normally used is also a necessary part of these procedures.

The polar interferometer system is aligned as follows:

1. Move the carriage to the rear and position the gage block between the interferometers by turning the knob (Item 1021-F, Figure 42). Adjust the gage block to a position that is approximately $3/32$ inch from the periphery of Item 1024-A, Figure 41.
2. With a spanner wrench, rotate Item 1024-A on its axis until an image of the gage block surface is observed. The check nut (Item 1024-D) is kept moderately tight during this adjustment.
3. Using the differential screw adjustment (labeled PIC-BG-9, Figure 41), search for fringes. When the bull's-eye fringes appear, they may not be coincident with cross hairs. The objective now is to align the dot of the bull's-eye coincident with the cross-hair reticle of the eyepiece. Vertical adjustment in alignment may be made with Item 1024-A; horizontal adjustment may be made with the two Size 0-80 set screws on the end plate of the cube prism beam splitter. The Size 0 set screws position the cube prism angularly on an axis perpendicular to the plane of the drawing.
4. After acceptable fringes are obtained, the carriage is moved forward to intercept the polar diameter of the sphere. If the sphere and the gage block are of near equal length (which is recommended), search for fringes in one instrument using the differential screw (Item 1024-H, Figure 41). Fringes may not be coincident with the cross hairs.

Adjust the differential screw of the undercarriage and traverse adjustment until the bull's-eye fringe is coincident with the cross hairs in one instrument.

Search for fringes in the other instrument using the adjustment screw (PIC-BG-9). Adjust the alignment using the $1/4$ -inch cap screws (leaving a slight tension), securing Item 1023-B to Item 1023-A. Move the assembly to align the dot on the vertical cross hair. Retighten the cap screws. If the dot is not coincident top to bottom, loosen (leave slight tension) the Type 10 clamping screw in Item 1025-A and move the whole instrument forward or backward to bring the dot coincident with the horizontal cross hair. Retighten the Type 10 clamping screw.

It may be necessary to repeat this alignment procedure to produce optimum results. The system is completely aligned when the dot of the bull's-eye fringes is coincident with the cross hairs in both instruments.

EXHIBIT B

DESCRIPTION AND OPTICAL ALIGNMENT OF THE CUTTERHEAD INTERFEROMETER

The cutterhead interferometer system shown on Drawing MR-102, Figure 43, fulfills the following needs:

1. Steps "S" (Figure 37) are measured between two spherical surfaces to ascertain the coincidence of centers, as described in Exhibit C, Page 98.
2. Depth of cut is measured, a vital function when setting the tool for the final cut, as described in Exhibit D, Steps 10 and 16.
3. "Stop" position of the cutterhead at the pole is determined in Step 10 (Exhibit D), and the proper tool height is set for the desired cut.
4. Axes of the work and the cutterhead spindles are aligned, as described in Phase I, Page 39.

Mechanical Description

The section shown at the lower left, Figure 43, depicts the assembly in a machining operation with the tool (diamond knife) at the north pole of a sphere. In this view, the tool (chisel-shaped element below Item 1014-G) is mounted on the cutterhead spindle of the experimental apparatus. The spindle controls the position (in micro-inches) of the cutting edge of the diamond knife relative to the sphere.

Initially, the diamond tool is located some distance from the sphere. To bring the edge of the tool near the cutting position (screw threads on Adjusting Nuts 1014-A and 1013-C), the coarse feed is used.

Rotation of the hand wheel (Item 1014-P) urges the nuts (Item 1014-K) along the axis of the screw (Item 1014-L) for fine adjustment. Wedges (Item 1014-J) are located between the nuts and move with the nuts. The taper^(o) of the top wedge is opposite the taper of the bottom wedge. Thus, that part of the assembly suspended

(o) Wedges were tapered to produce a 150-microinch displacement per full turn of the hand wheel. Therefore a 2-degree rotation of the hand wheel produces one microinch in displacement.

on flexures (Item 1014-R) must move either up or down with respect to the mounting block (Item 1013-A). The slot is Item 1013-A, the wedge surfaces (Item 1014-J), and the projection on Item 1013-B are lapped to near the gage-block finish. The fitup is similar to a stack of gage blocks. This arrangement eliminates any clearance or lost motion. The wedges have a carbon surface which makes such an assembly functional. Since the diamond tool is attached to the flexure suspended assembly, the two move in unison.

The differential nut for positioning the interferometer comprises three parts (Items 1014-C, -D, and -E). When rotating Item 1014-E, the interferometer moves rapidly; when the parts are rotated together, slow motion is imparted. Since interferometer adjustments are independent of the tool-positioning adjustments, interference-fringe adjustments can be made without altering the tool position.

Optical Description

The optical system is composed of a white-light interferometer placed between the objective lens of a microscope and the work. Figure 43 shows a tungsten lamp which illuminates the pinhole (Item 1015-F) enclosed in a housing (Item 1015-C). Light from the pinhole projects through the condensing lens and is directed into the cube-prism beam splitter where the light beam is split into two components. The transmitted component focuses on the reference surface (Item 1015-B), while the reflected component focuses on the work surface in front of the cutting edge. Both components are reflected to the beam splitter where they recombine and proceed into the microscope.

When the optical distances in each component are almost equal, the two components interfere, producing colored fringes in the field of the microscope. Where the components are exactly equal, destructive interference occurs, producing a so-called black fringe. Movement of the work surface toward or away from the interferometer system causes a movement of the black fringe. Also, all the colors of the spectrum will be seen in the field. The colored fringes represent a means for measuring displacement. Details of white-light interferometry are covered by many textbooks. (p)

Figure 44 shows bull's-eye fringes typical of this system. These fringes develop in front of the cutting tool. The height of the step between the fringes is a measure of the depth of cut being taken by the tool. The red fringe is used as a reference.

(p) Such as Fundamentals of Optics by Jenkins and White.

Figure 44. BULL'S-EYE FRINGES ON THE CUTTERHEAD INTERFEROMETER.

Distance between two red fringes is 12.3 microinches. Since the step height is about two thirds of a red-fringe spacing, the tool is removing about 8 microinches from the sphere surface. The scale reticle in the microscope eyepiece is useful in measuring the step height and fringe spacing.

Optical Alignment

Optical alignment is initiated after the mechanical assembly is complete and functioning properly.

Referring to Figure 43, the assembly is mounted on a granite surface plate with the optical axis parallel to the plane of the surface plate. All optical components are installed, but the tool is omitted.

An autocollimator, square to the granite surface plate, is trained on the vertical face of the cube-prism beam splitter. With a chisel-shaped plastic or wooden rod bearing on the steel end plates of the prism, the prism is gradually rotated on an axis vertical to the plane until the face is at a right angle to the surface plate, as indicated by the autocollimator. (Antireflection coatings on the prism surface make it necessary to read the image in the autocollimator in a darkened room.)

Adjust the microscope eyepiece to bring the reference surface (Item 1014-A) into sharp focus. Adjust the light source (Items 1015-C, -D, and -F) by moving it along the optical axis until a sharp image of the pinhole is seen in the microscope. (Pinhole image is reflected from the reference surface.)

A vertical reflecting surface is mounted on the surface plate perpendicular to the optical axis, as seen through the microscope tube. (The mounting surface in Item 1013-A may be used as a reference.) Move the reflecting surface along the optical axis until it comes into sharp focus. Then, with the differential nut (Items 1014-D and E), search for the white-light fringes. Fringes may appear crowded. Tap the steel end plate on the cube-prism beam splitter with a plastic rod to rotate it about a vertical axis with respect to the plane of the drawing until a maximum spread of fringes is observed. The reference surface is mounted to permit a small angular motion on an axis parallel to the microscope. By adjusting the small cap screws securing the reference surface, the fringes can be spread further. Alternating adjustments will produce one fringe covering the entire field, the optimum adjustment.

A note of caution is made with respect to the selection of the cube-prism beam splitter. In Exhibit H of Phase II, Section 3 (Page 171), two assembly conditions are discussed. A prism with a single black fringe must be selected for this instrument.

EXHIBIT C

ELEVATING MECHANISM FOR THE CUTTERHEAD SPINDLE

The machining process used for the spheres required a mechanical adjustment to align the axis of the cutterhead spindle with the precise center of the hemispherical surface formed by the initial machining operation. The mechanism to accomplish this is shown on Drawing MR-100; Figure 45. A schematic, Figure 35, shows the important features. The sphere has more than one half its surface finished to the final size by the initial machining operations. The objective is to finish the remaining surface to the same diameter and center as the first machined surface. Therefore, the axis of the cutterhead spindle must intersect Point 0, the center of the volume generated by the spherical surface already in hand.

As shown, the sphere is mounted on the nose of the work spindle with Point 0 coincident with the work spindle axis. The runout of the surface already formed was measured with the cutterhead interferometer and found to be less than two microinches. The axes of the cutterhead and work spindles intersect by virtue of the original alignment of the machine and this alignment is maintained or the height of the cutterhead spindle is adjusted. Height of the cutterhead spindle is adjusted to intersect at Point 0 as follows:

The cutterhead interferometer is maneuvered to any position on the existing spherical surface where it is adjusted to show interference fringes. With the hand wheel, the whole cutterhead spindle assembly is raised or lowered until the fringes in the cutterhead interferometer indicate no displacement when scanning the finished spherical surface. A trial cut is then made over the unfinished portion of the sphere.

Referring to Figure 37 and the polar interferometer system described in Exhibit A, two independent determinations of $D + S$ must be made. For perfect alignment, $\underline{D + S}$ as measured with the polar interferometer system must equal $(D + S)$ as determined by measuring the diameter at the equator and adding the step (S) as measured with the cutterhead interferometer. If $\underline{D + S}$ is greater than $(D + S)$, the axis is too low. Usually the difference encountered between $\underline{D + S}$ and $(D + S)$ is 10 to 20 microinches because the height has already been estimated by scanning the existing spherical surface.

Figure 35 depicts the elevating mechanism. The mechanism is in symmetry with the cutterhead spindle axis. The eminent features of this mechanism are the hydrostatic gas bearings and the flexure-type guides. Gas bearings permit height adjustment without the erratic effects of friction typical of conventional bearings. The restraint afforded by the flexures (Item 1016-B) keeps the axis properly oriented and aligned, and permits elevation of the spindle assembly over a range of 0.020 inch with a reliability of a few microinches.

The hydrostatic gas bearings also function to retract the tool (diamond knife) from the work when the cutterhead returns to the cut starting position. In Figure 35, the view is from the operator position. Cutting starts at the pole, as shown, with no gas to the adjustment bearings. When the cut is terminated near the equator, gas is supplied to the bearings on the side opposite from the operator. The resulting displacement of the cutterhead spindle assembly permits the tool to return to the pole without contacting the work. At the pole, the tool is fed downward for the subsequent cut. Gas is turned off and the work spindle drive is engaged for the cut. (When adjusting for height, gas is supplied to all bearings.)

EXHIBIT D

MACHINING SPHERES

Procedure for Machining Spheres

The procedure for machining spheres is as follows:

1. Spheres of Type 2014 aluminum alloy, zero temper, are machined to a 4.030-inch diameter by conventional shop practice. Special attention is given to the last 1/16 inch of stock removed by using sharp tools and fine cutting feeds to minimize machining stresses.
2. The holding fixture (Item MRX-1074-A, Figure 36) and the sphere are cleaned with a commercial solvent.
3. Sphere and fixture are heated to between 200 and 250° F with an electric heat gun. Special wax (Stickum 170) is applied to the surfaces of sphere and fixture. Insert the sphere in the fixture and apply additional heat until a uniform meniscus is observed at the joint between the sphere and fixture. Cool the assembly to room temperature. Remove any excess wax with a solvent, such as xylene.
4. Mount the sphere with the fixture on the nose of the work spindle using eight Size 10 cap screws. With the dial indicator, center the sphere to the axis of rotation of the work spindle to the nearest 0.001 inch.
5. Using the tungsten carbide tool (lapped cutting edge) and olive oil as a lubricant, turn the first half of the spherical surface to 4.001 inches in diameter using conventional micrometers as the measuring instruments. The work spindle speed is set at 2,000 rpm. The first two cuts are made 0.005 inch deep with a feed rate of 0.002 inch/revolution of the work spindle. With a newly lapped cutting edge, machining is continued with cuts 0.001 inch deep and a tool feed rate of 0.001 inch/revolution until the size of 4.001 inches is reached.
6. Remove the sphere and fixture from the work spindle.
7. Heat the assembly to between 200 and 250° F using the heat gun, and demount the sphere from the fixture.
8. While the sphere is hot, apply special wax to its newly turned surface. Heat and apply wax to the second fixture (Item MRX-1074-B, Figure 36). Join the sphere and fixture and apply additional heat, if necessary, to form a uniform meniscus at the joint. Cool to room temperature.

9. Repeat Step 5.
10. Replace the tungsten carbide tool with a diamond knife. Using the microscope of the cutterhead interferometer, set the tool on the axis at the pole, where the finish comes to a point. Using this point as a reference for the tool setting, advance the diamond knife to cut 25 to 50 microinches deep at the pole. The work spindle rotates at 2,000 rpm; tool feeds at 0.001 inch/revolution. Turn approximately 200 degrees of spherical surface, using olive oil as lubricant; stop at the end of a cut. Apply gas to the bearings of the elevating mechanism to retract the diamond knife.

Return the knife to a position about five degrees short of the pole. Turn off the gas to the bearings and advance the knife about 10 microinches, making a cut of two or three degrees. Stop the feed and spindle, and set the cutterhead interferometer for a bull's-eye fringe system. There will be a step in the fringes, as indicated in Figure 44.

Restart the spindle and slowly feed the knife toward the pole, observing fringes in the cutterhead interferometer. When the step in the fringes disappears, stop the feed and set the stop micrometer. Apply gas to the elevating mechanism of the cutterhead spindle to retract the knife. Advance the knife about 75 microinches, adjusting the micrometer stop to control the end of the cut near the equator, about 0.010 inch short of the previous cut.

Turn off the gas to the bearings of the elevating mechanism and immediately engage the tool feed cutting up to the micrometer stop at the equator. Apply gas to the elevating mechanism and return it to the pole position. Apply the dynamic balancing procedures described in Phase I, Pages 36 through 39.

Continue the machining sequence until about 100 microinches of material remains. Measure the diameter with an OD interferometer system (Phase I, Pages 49 to 51). Take two cuts approximately 40 microinches deep. There should be approximately 20 microinches of material left for the final cut. Diamond-knife adjustment for the final cut is equal to one half the difference between the final size and the immediate diameter measurement. Control the adjustment by reading the fringes in the cutterhead interferometer, shown in Figure 44.

11. Remove the fixture with the sphere from the work spindle.
12. Heat the fixture and sphere to between 200 and 250°F with a heat gun. Apply wax to the newly finished surface. Exercise care with respect to cleanliness. Turn the sphere 180 degrees in same fixture to expose the unfinished surface. The same fixture is used for two operations. Variations in the wax film thickness will accommodate the difference in diameter. Cool to room temperature.

Commercial, medical-grade cotton is used to handle the hot sphere without damaging the surface.

13. Remove the OD interferometer system and replace it with the polar interferometer system.
14. Remove any excess wax from the fixture and sphere with xylene.
15. Remount the fixture with the sphere on the work spindle using Size 10 cap screws. Rough center the sphere to make it concentric with the work spindle using the electronic indicator. The stylus should bear on an unfinished surface. Make the final centering using the cutterhead interferometer as it looks at the finished surface of the sphere near the equator. Runout should not exceed two microinches.
16. Repeat the machining process described in Step 10 except for the cutterhead micrometer stop procedure which is eliminated. The stop at the pole is already set while the one at the equator is not used. Diameter measurement made with the polar interferometer is directly related. For example, a size of 4.000020 inches read from the polar interferometer system means that the diamond knife must be advanced 20 microinches (1.7 red fringes in the cutterhead interferometer) to make the final cut for 4.000000 inches, the final size.
17. Remove the fixture with the sphere from the work spindle.
18. Heat the fixture and sphere to between 200 and 250° F. Demount the sphere using medical-quality cotton for handling.
19. Remove the wax with xylene using a cotton swab.

EXHIBIT E

MACHINING AND MEASURING A SPHERE HOLDING FIXTURE

At the beginning of these studies, the detail requirements of the sphere holding fixture were not known. It was thought that holding problems might require very accurate internal surfaces to match the external spherical surface of the test spheres. Thus, expediency dictated that the machining and measuring capability be accurate within the microinch range to control the spherical surface of the holding fixture.

The machining and measuring system provided is shown in Figure 38. With the cutterhead interferometer described in Exhibit B, measuring and tool mounting devices are designed into a single system. The interferometer is an adaptation of the point interferometer used in the cutterhead of the Phase I studies. The microscope objective is replaced with a Bausch and Lomb 48-millimeter objective. Two additions, a light source holder (Item 1011-F) and a reference surface holder (Item 1011-G), complete the modification to the interferometer.

The main structural element of the system (Item 1011-A) is fitted to the original cutterhead slide (Items 820M110-A and -B). Slide movement provided by a differential screw mechanism (a nut, Item 1011-B and a thrust plate, Item 1011-C) advances the tool to the work. Interferometer position adjustment is made with a differential nut (Item 1011-D). Tool mounting is provided by a holder (Item 1011-E). A separate component (Item 1012-A) is provided to establish an accurately known radius for the internal spherical surface.

The following is a description of the machining operations used to turn an accurate internal spherical surface in the sphere holding fixture (Items 1074-A and -B, Figure 36). The fixture is machined initially by conventional shop practices to all dimensions shown with the exception of the internal radius. About 0.015 inch of stock is left on the sphere for finishing. Before mounting, the plane surface of the fixture is mounted, using eight Size 10 cap screws lightly and evenly tightened, and centered on the work spindle using a dial indicator. Positioning of the fixture is accomplished by tapping with a plastic hammer. The cap screws are tightened to an even torque. A curved-edge diamond tool is set with its cutting edge centered on the reticle of the interferometer eyepiece (see Item 1011-E, Figure 38). Using a nut (Item 1011-B), the tool is set for cutting, and speed is adjusted to 2,000 rpm. Light cuts are made on the internal surface until a high-quality finish is achieved. Using another nut (Item 1011-D), the interferometer is adjusted to produce a zero-order fringe at the newly machined surface. From this point on, no further adjustments are made to the interferometer.

A 0.250-inch gage block is wrung to the auxiliary piece (Item 1012-A), shown in Figure 38, and placed on the nose of the work spindle. At this time, the hemisphere measuring system, shown in Figure 10, Phase I, must be brought into action. A

gage block combination equal to 4.500000 inches is set up and the diameter gaging interferometers are set to this gage length. The interferometer carriage is moved forward until the interferometer centerline intersects the work spindle axis. Demount the tool holder (Item 1011-E) and position the cutterhead vertically. Turn the work spindle manually, using the drive belt, until the gage block is perpendicular to one of the interferometers of the hemisphere measuring system and adjust the undercarriage differential screw to obtain the fringes. (Do not touch the position adjustment on the interferometers.)

Rotate the work spindle 180 degrees until the gage block faces the other interferometer. Using the undercarriage adjustment, search for fringes. If the fringes in the second interferometer move away from the axis of rotation of the work spindle, the component (Item 1012-A) is rotating on too large a radius. Decrease the distance between the gage block and the work spindle axis to obtain the proper radius.

When a zero-order fringe in the interferometers is coincident with the cross hairs without an adjustment of the undercarriage, the inside of the 0.250-inch gage block represents a diameter of 4.000000 inches. The cutterhead is turned, with its lengthwise axis in a horizontal position, to face the inside of the gage block. Using the nut (Item 1011-B), search for zero-order fringes and adjust it coincident with the cross hairs. From this point on, no adjustments are made on the cutterhead.

The tool holder (Item 1011-E) is replaced so that the edge of the tool is coincident with the eyepiece reticle. The edge of the tool is adjusted to cut a diameter of 4.000000 inches. The elevating mechanism, described in Exhibit C, must now be adjusted to its greatest height. Preparations are now complete; finishing of the internal spherical surface may be started.

The work spindle is set in motion at 2,000 rpm and the cutterhead feed adjusted to 0.001 inch/revolution of the work spindle. The tool is advanced for subsequent cuts by lowering the elevating mechanism. Any attempts to adjust the feed via the cutterhead will destroy the 4.000000-inch diameter already set into the equipment. With moderate attention to temperature, it is estimated that radii cut in this fashion are accurate to within 25 microinches. With the ultimate in temperature control, it is estimated that radii could be cut accurately to within 5 to 10 microinches.

EXHIBIT. F

ALIGNMENT OF THE POLAR INTERFEROMETER

The polar interferometer must be optically aligned before the instrument is inserted into the measuring system. The procedure is as follows:

1. Working on a granite surface plate, clamp the barrel (Item 1024-B, Figure 41) in the V block with the 0.375-inch-diameter hole in the periphery of the barrel in the upward position.
2. Assemble the light-source holder (Item 1024-F) over the barrel locating the 0.375-inch-diameter central hole concentric with the hole in the side of the barrel (insert a 0.375-inch-diameter dowel pin through both holes). Tighten the cap screw (Item 1024-F). Remove the dowel.
3. Install the light source assembly (Figure 46).

Note: This drawing is adapted from a part of Drawing MRX-1003.

Figure 46. LIGHT-SOURCE ASSEMBLY.

4. Install the beam-splitter assembly (Item 1024-C, Figure 41) in the barrel (Item 1024-B).

5. Install the Bausch and Lomb 48-millimeter microscope objective.
6. Install the check nut (Item 1024-D) and extension piece (Item 1024-A). Tighten the check nut with the opening in the vicinity of the cube-prism beam splitter, facing to one side.
7. Turn on the light source and adjust the beam-splitter assembly (Item 1024-G) to project the beam through the extension piece.
8. Install the 3/16-inch cube-prism beam splitter and Size 0-80 TPI set screws. Using the indicator, adjust the face of the cube prism parallel to the periphery of the extension piece (Item 1024-A).
9. With a right-angle block, set on the granite surface plate, orient the vertical face of the block parallel to the periphery of the extension piece, but removed a distance of 3/32 inch.
10. Insert the microscope eyepiece and search for an image of the vertical surface of the right-angle block by turning the entire assembly in the V block.
11. Focus the light source (Figure 46) by moving Item 1003-E in or out to produce a sharp image of the pin hole. This image is reflected from the vertical surface of the right-angle block.
12. Turn the entire assembly in the V block to place the pin-hole image coincident with the horizontal cross hairs.
13. Adjust the Size 0-80 set screws to turn the cube-prism beam splitter on an axis perpendicular to the plane of the drawing. The prism is properly adjusted when the pin-hole image is coincident with the vertical cross hairs.
14. Install the reference surface having a 1.7-inch convex radius and adjust along the lengthwise axis to produce fringes.
15. Move the reference surface up or down, left or right with respect to the lengthwise axis to align the dot of the bull's-eye fringe system coincident with the cross hair. Tighten the Size 2 cap screws.
16. Remove the V block clamp.
17. Remove the eyepiece and light source (Item 1024-F).
18. Insert the remaining interferometer assembly through the mounting (Item 1025-A), then through the light source (Item 1024-F), and tighten the clamp. Install the eyepiece.

Final alignment of the interferometer is discussed in Exhibit A.

The 3/16-inch cube-prism beam splitter is aligned according to the procedures described under Exhibit H of Phase II, Section 3, Page 171. Two conditions of alignment are described, but the condition applying to the cube prism provides one black fringe. However, the fringe system observed in the polar interferometer shows two dark fringes instead of one. This inconsistency is the result of phase differences in the interfering light. The prism is assembled with white light entering the system from the blind face relative to the assembly of the polar interferometer. But light enters the prism assembled in the polar interferometer system from the same face as it is emitted; that is, on the opposite side of the beam-splitter coating. Additional work will be necessary to determine the reason for the inconsistencies.

When the instrument was initially assembled, unforeseen disadvantages were encountered; namely, the image was lacking in contrast and the fringes had poor color quality. Subsequent work proved that the poor image contrast was the result of back reflections from the light source entering the instrument along the same axis as it is viewed. The color defect was the result of a difference in polarization between the split beams. Satisfactory fringes were produced by: (1) coating all air-to-glass surfaces with antireflection coatings, and (2) polarizing the light emitted from the source so that maximum light entering the eye was in a condition to interfere. Further work is necessary to determine the accuracy of the statement relative to polarized light.

PHASE II, SECTION 3

HEMISHELL TURNING MACHINE

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INTRODUCTION

Experience with the hemisphere turning machine made it evident that for further advances in the machine-design study, a new apparatus was needed that embodied new concepts, particularly for temperature control. It was decided to build a new and more versatile experimental machine that would handle work with more complex and delicate test pieces—in particular hollow hemispheres or hemishells—and that would be suitable for studying machining-measuring processes for a greater range of sizes than that for which the hemisphere machine was designed. The technology developed in Phase I and the earlier work in Phase II justified this decision.

The new research machine—known as the hemishell turning machine—and some of the results obtained with it are the subject of this section of the report.

Some detailed information concerning the design of the major components of the hemishell turning machine, fabrication techniques, and operating procedures used in building and working with the machine is given in Exhibits A through L.

DESIGN CONCEPTS

TEMPERATURE CONTROL

Design Criteria

Microinch dimensional control of the machining process is dependent on temperature control whenever the materials of the system possess a significant coefficient of thermal expansion. Since shape and size are functions of temperature for a bulk of the engineering materials, the technology of microinch machining must deal first with temperature control.

Two approaches to temperature control are possible:

1. Critical temperatures may be measured and the size and shape achieved by making compensations for deviations from standard conditions. (This is the approach taken in Phase I and the turning of hard materials and spheres in Phase II.)
2. Critical temperatures may be controlled and maintained at a standard set point. (This approach was taken in the development of the hemishell turning machine.)

Of the two kinds of temperature control, the second is the more desirable. Temperature control in this case is inherent in the design of the apparatus. Control by measurement and compensation depends on the skill of the machine operator to make the proper compensation, if indeed this can be made.

To provide temperature control, one must first identify all heat sources and heat sumps. The following guides may then be used in dealing with the temperature problems resulting from such heat sources and sumps:

1. Eliminate or Minimize - All heat sources or heat sumps must be eliminated or minimized through the selection of the lowest heat-energy devices.
2. Dissipate - Where complete heat-source elimination is not possible, excess heat should be dissipated through a heat-conducting mechanism.
3. Isolate - Necessary devices (heat sources or heat sumps) should be isolated from critical parts of the apparatus if possible.

These three criteria were applied to all critical temperature control areas within the hemishell turning machine, shown in Figures 47 through 49.

Machine Structure

The machine structure is divided into two major components, the main casting and the base, shown in Figure 49 as 1029 and 1033, respectively. The base provides an enclosure for the necessary heat-producing elements—the work-spindle drive motor, the cutterhead-spindle drive motor, and a solenoid valve to control the gas supply.

The main casting is mounted on the base through a three-point suspension of kinematic design (Drawings MR-1044-B, -D, -E, and -F). Placed between these two castings is a heat shield, MRX-1033, Figure 50. With reference to Figure 49 (Item 1046-A), a six-inch-diameter hole is machined (not shown) with its center coincident with the rotational axis of the motor. A six-inch-diameter flexible plastic tube is connected at the hole with the other end attached to a 170-cfm exhaust fan venting to the exterior of the machining room. The air inlet to the base is through a six-inch-square hole cut in the gas-pressure control panel shown in Figure 50 (MRX-1035). Thus, a large part of the heat developed in these necessary power sources is removed from the machining-measuring system, optimizing the extent of the temperature control.

Applying the temperature-control criteria to the machine structure, it will be noted that:

1. Eliminate or Minimize - The smallest adequate work spindle and cutterhead drive motor were selected, thus minimizing the heat source.

Figure 47. HEMISHELL TURNING MACHINE – OPERATOR SIDE.

Figure 48. HEMISHELL TURNING MACHINE – BACK SIDE.

2. Dissipate - The heat shield inserted between the base and main casting serves to dissipate any radiated heat originating at the electric motors and prevents it from reaching the critical machine components. The exhaust fan removes the cooling air from the electric motors.
3. Isolate - The electric motors are enclosed in the noncritical machine element, the base. The kinematic mounting of the main casting on the base isolates the effect of any thermal distortions that occur in the base.

Work Spindle

To apply the temperature-control guidelines to the work spindle, it is first necessary to look at its mode of operation. The general usage of the hemishell turning machine requires spindle speeds ranging from 300 to 2,000 rpm. As previously stated, the temperature-control requirements dictate that temperature variations be maintained within $\pm 0.1^\circ \text{F}$ regardless of the spindle speed.

The mechanical design of this spindle requires a back-to-back thrust bearing, as shown in Figure 51. This arrangement minimizes the distance between the thrust faces, a condition which minimizes the effect of axial deviations resulting from temperature variations. Phase I showed that axial deviations, resulting from temperature variations, were critical and that the heat generated at the thrust bearing had a great influence on the work temperature and axial position of the work. Therefore, complete control of microinch machining processes requires that heat, resulting from the shearing of the gas film in the thrust bearings, be dissipated without upsetting the standard temperature conditions of the critical machine areas:

Applying the criteria for temperature control:

1. Eliminate or Minimize - The hydrostatic, gas-lubricated bearing produces the minimum thermal disturbance to established temperature conditions.
2. Dissipate - Seventy-two, 1/8-inch-diameter holes were drilled radially through the body of the thrust bearing (Drawing MR-1037-A, Figure 52). The passages provided by these holes conduct a liquid which maintains the spindle temperature at standard conditions.
3. Isolate - Mechanical considerations prohibited the complete isolation of the heat source in this instance.

Machining Operation

Data developed during the Phase I machining studies showed that the total heat input, during the critical turning operations, was less than 1 Btu/min when using

Figure 50. HEAT-DISSIPATION SYSTEM FOR THE HEMISHELL TURNING MACHINE.

Figure 51. WORK AND TOOL SPINDLE CARRIAGE DRIVE ARRANGEMENT FOR THE HEMISHELL TURNING MACHINE.

Figure 52. WORK SPINDLE DETAILS.

a diamond knife with a depth of cut of 100 microinches or less, and a tool advance of 0.001 inch/revolution for speeds up to 2,000 rpm. When making the final turning operations at 2,000 rpm with a depth of about 20 microinches or less and a tool advance of 0.001 inch/revolution, the total heat input is estimated to be between 0.1 and 0.2 Btu/min.

Microinch control of the machining operation, therefore, requires a dissipation of about 1 Btu/min, which is the heat liberated by the energy of cutting. This heat must be dissipated by a temperature difference of about 0.2°F between the work and any coolant used. Using cutting oil with a specific heat of $0.5\text{ Btu/lb}/^{\circ}\text{F}$ as a coolant, (q) a flow of about 1.2 gpm would be required to dissipate all of the heat.

While provision for delivery of 1 qt/min of coolant oil at 67.8°F was feasible, a delivery of 1.2 gal/min was too large a quantity to handle. Consequently, in the semifinishing operations with this machine, the work was allowed to rise 1°F . A flow of 1 qt/min was sufficient to handle the temperature-control requirements for the final turning operations.

Applying the criteria for temperature control:

1. Eliminate or Minimize - The diamond-knife cutting tool minimized heat generation.
2. Dissipate - The temperature-controlled oil coolant performs this function adequately.
3. Isolate - The heat is developed at the work, a critical part of the system, and is therefore impossible to isolate.

Main Casting

Phase I had indicated that the relative position of the critical mechanical components (the work spindle and the cutterhead spindle) was not reliable within a few microinches over long periods of time because of dimensional distortions caused by thermal gradients in the range of 0.2 to 0.3°F . These gradients resulted from heat radiated by the operating personnel and electric motors. This situation slowed the

-
- (q) Water or water-soluble coolants were not considered because of their relatively high evaporation rates, which make temperature controls of $\pm 0.1^{\circ}\text{F}$ practically impossible.

pace of the work considerably and limited the ultimate accuracy of the machined parts. To keep the Phase I apparatus in a usable working condition, frequent adjustments were required to compensate for these temperature deviations.

In Phase II, this disadvantage was overcome by circulating water through the cavity in the main casting (Figure 50). Figure 53 shows the cavity and water-circulation path. The capacity of this cavity is approximately 25 gallons (200 lbs).

Figure 53. CAVITY IN THE MAIN CASTING AND DIRECTION OF LIQUID FLOW.

Applying the criteria for temperature control:

1. Eliminate or Minimize - Deviations in temperature were minimized by operating in an air-conditioned laboratory.
2. Dissipate - Circulation of water at a controlled temperature through a cavity in the main casting dissipates any excess heat.
3. Isolate - This requirement cannot be met because the main casting is a fundamental part of the system.

Gage Block

The dimensional standard for the machining studies was a gage block calibrated at 68.0° F by the National Bureau of Standards. When referring to temperatures other than standard, compensation must be made for thermal expansion. Operating at a nonstandard temperature slows the experimental procedures because of the time required to make gage-block temperature measurements and calculations. In the interest of expediency and accuracy, the gage-block temperature was maintained at 68.0° F.

The gage block was enclosed, except for its gaging ends, in a copper container through which water, maintained at a temperature of 68.0° F, was circulated.

Applying the temperature control criteria:

1. Eliminate or Minimize - The air-conditioned laboratory meets this requirement.
2. Dissipate - Circulation of water at a controlled temperature meets this requirement.
3. Isolate - The copper enclosure serves a two-fold purpose in that it isolates as well as dissipates.

MECHANICAL CONSIDERATIONS

Basic machining concepts for the Phase II apparatus are essentially those of Phase I with minor modifications. Notable differences are discussed in the sections that follow.

Attitude

The attitude of the workpiece in the Phase II machine is displaced 90 degrees from that of the Phase I machine. In the Phase I machine, the work-spindle axis is vertical and the cutterhead axis is horizontal; in the Phase II machine, the work-spindle axis is horizontal and the cutterhead axis is vertical. This change maintains a constant orientation of the gravitational force on the outside-diameter centering interferometer component. If the attitude of the Phase I machine had been used, a varying gravitational force would have existed which would have cast doubt upon the reliability of measurements to an accuracy of a few microinches.

Distance

Distance from the axis of the cutterhead spindle to the face of the work spindle is adjustable over an eight-inch range. This distance is necessary for multistage machining processes. Furthermore, the range of adjustment permits machining processes for spherical surfaces of from two to eight inches in diameter.^(r) This adjustment was made possible by the installation of very accurate V ways to provide the required linear motion.

(r) A similar adjustment, in increments of 0.020 inch, was provided through modification to the hemisphere turning machine for sphere-turning studies; but the 0.020-inch range was too limiting to consider the equipment versatile.

Spindle

The Phase II work spindle is a two-piece design, rather than the single piece used for Phase I. This modification was necessary to bring about a compact thrust bearing element which minimized the thermal problems.

Design Changes

Several mechanical design changes were required to provide a system for circulating a heat-dissipating liquid. These changes included such features as the cavity in the main casting and the two-part design of the main structures to allow for the insertion of the heat shields (Figure 50).

METROLOGY SYSTEMS

Metrology design concepts used for the Phase II apparatus embody practically all of those used for the Phase I machine in addition to those required to qualify internal spherical surfaces and relate the center of an external spherical surface to the center of the enveloped spherical volume.

The outside-diameter measuring system is basically like the Phase I system. However, the change in the attitude of the Phase II apparatus necessitated the design of an entirely new mechanical system (Figure 54).

Inside-diameter measurements also follow the same basic concepts as those used in the Phase I work; ie, the transferral of a gage-block dimension to the inside diameter of the workpiece via an interferometer system. The outside-diameter measuring units are used for inside-diameter measurements by making two modifications:

1. The interferometers are remounted to alter their attitudes by the use of a special bracket (Item 1037-A, Figure 55).
2. The light paths are altered to direct the measuring beam toward the inside surface with an auxiliary piece (Item 1037-C, Figure 55).

Figure 55 shows the arrangement of this system. Three additional interferometers are provided for the hemishell apparatus: (1) an outside-diameter cutterhead interferometer, shown in Figure 56; (2) an inside-diameter cutterhead interferometer, shown in Figure 57; (3) a centering interferometer, shown in Figure 58.

The outside and inside cutterhead interferometers serve a twofold purpose: (1) provide a mounting for the cutting tool (diamond knife); (2) are measuring devices to determine the amount of material being removed in increments as small as two micro-inches.

The centering interferometer determines the coincidence of the center of the volume generated by the inside spherical surface to that generated by the outside spherical surface through the use of the axis of rotation of the cutterhead spindle as a reference.

WORK-HOLDING DEVICE

The work-holding methods required for this work must have characteristics not typical of conventional holding methods. For this experiment, the holding device must have a configuration that permits access to both inside and outside surfaces of the hemishell. This access is required to accurately fix the position of the spherical surfaces relative to the work-spindle axis. The holding device must also fix the position of the work piece without strain and without marring the surface.

Three methods were initially considered: (1) vacuum, (2) optical contact, and (3) adhesion with a special wax. The third method was selected because it appeared to satisfy the requirements in the simplest manner and involved a minimum development effort and cost.

Figure 59 shows the salient features of the holding technique. The holding fixture (Figure 60) is turned with a diamond knife so that its spherical radius mates with the inside diameter of the hemishell and leaves a 0.001-inch radial clearance. The wax film between the hemishell and the holder serves a twofold function: (1) it acts as an adhesive when solidified, and (2) it acts as a lubricating film in its liquid state, preventing physical contact between the mirror-like surfaces of the hemishell and the holder. A two-part adjustable aluminum parallel (Figure 59) is used to align the face of the hemishell perpendicular to the axis of the holder.

The enclosure is composed of a 6-inch-diameter copper cylinder having a 1/4-inch wall thickness, a 7-inch-diameter by 1/4-inch-thick copper cover, and a 7-inch-diameter by 1/2-inch-thick copper base plate. This enclosure minimizes thermal gradients. The small fan is used to minimize the thermal gradients in the space surrounding the copper enclosure. This entire assembly is located in an electric oven.

The thermal expansion coefficient of the holder material must be very nearly identical to that of the hemishell material. In the case at hand, the holder was made from the same bar of material as the hemishell.

The assembly is heated in the electric oven to a temperature of 173° F at which temperature the wax, previously applied to the holder, becomes liquid and produces a lubricating film approximately 0.001 inch thick between the holder and the work-piece. The thermal linear expansion coefficient of the wax was measured to be

Figure 59. HEMISHELL MOUNTING TECHNIQUE.

about eighteen times as great as that of the Type 2014 aluminum alloy. If it is assumed that the wax solidifies at 100°F , a calculated strain of three microinches is produced by the differential coefficient of linear expansion upon cooling the entire assembly to 68°F .^(s)

The major objective in minimizing thermal gradients is the elimination of locked stresses between the holder and hemishell. Any significant strain resulting from such stresses will produce distortions and prohibit the attainment of the accuracies specified by the research objectives.

Eight cap screws around the base of the holder secure it to the work spindle. These screws are at a sufficient distance from the hemishell to isolate the localized strains around the cap screws. The work-spindle nose is quite rugged and capable of resisting the cap-screw strains without impairing rotational accuracy.

This holding concept is applied to both outside and inside machining processes.

(s) Tests show that the wax hardens gradually on cooling and, at approximately 100°F , is sufficiently solid to be considered a structural part of the holding system.

EXPERIMENTAL PROCEDURES

DIMENSIONAL TOLERANCES VERSUS THE MACHINING MEASURING PROCESS

Phase I established the machining processes for producing microinch accuracies in single-stage operations on relatively rugged shapes of soft material. To broaden the scope of these studies it was decided to carry out machining studies employing multistage operations on delicate shapes made of soft materials. A hollow hemisphere, or hemishell, made of Type 2014 aluminum alloy, zero temper, was selected for this study. For purposes of comparison, the size was in keeping with the past studies under Phases I and II. Dimensionally, the test part had a 4.500-inch outside diameter and a 4.000-inch inside diameter. The objective established, also in keeping with the Phase I and II studies, was to limit deviations of either the inner or outer surface from a true spherical surface to ± 15 microinches and to achieve concentricity of the outer and inner spherical surfaces to within ± 15 microinches.

The procedure chosen was to machine the external surface first and measure the diameter, and then to machine the internal surface and measure its diameter. The discussion that follows clarifies the reason for choosing this procedure.

A most important feature of this system is that diameter measurements can be made without stopping the rotation of the work spindle.^(t) A second check on the wall thickness is provided by the outside-diameter centering interferometer (Figure 58) and the inside-diameter cutterhead interferometer (Figure 57) in conjunction with the wall thickness gage-block holder (Figure 61). The wall-thickness measuring system is not considered an integral part of the measuring-machining process.

The three vital geometrical factors in dealing with the inside and outside surfaces are: (1) shape, (2) size, and (3) coincidence of the spherical centers. If the sum of the errors associated with each of these three factors falls within the tolerance envelopes previously described, the hemishell satisfies the tolerance goal.

To determine if the hemishell met the objective, measurements were made, as illustrated in Figures 62 and 63. These measurements were made during the course of the study on two different hemishells. Figure 62 represents the equator-to-pole-to-equator geometry; Figure 63 represents the equatorial geometry. To make the equatorial plot, measurements are taken at 90-degree increments about the polar axis. One plot at the equator would suffice for each hemishell after release from the holding fixtures.

(t) Alternate considerations required the work spindle to be stopped when making wall-thickness measurements.

BILL OF MATERIAL						
ITEM NO.	NO. REQ'D	DESCRIPTION	DRAWING NO.	MATERIAL	WIDTH THICK. OR DIA.	LENGTH

DECIMAL DIM. ± .0015"
FRACTIONAL DIM. ± 1/64"

NO.	DATE	REVISIONS	BY	CHKD. BY	REFERENCE DRAWINGS

E. I. DU PONT DE NEMOURS & COMPANY, INC.
EXPERIMENTAL STATION

TITLE MODIFICATIONS TO HOLDING
FIXTURE

DEPARTMENT ENGINEERING FOR _____

PROJECT NO. 56319 D.R. NO. _____

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DRAWING NO. MRX-1045

Figure 60. MODIFICATIONS TO THE HOLDING FIXTURE.

Figure 62. HEMISHELL EQUATOR-TO-POLE-TO-EQUATOR GEOMETRY.
(Scale within the Envelope - $0.1'' = 5\mu$)

Figure 63. HEMISHELL EQUATORIAL GEOMETRY. (Scale within the Envelope - $0.1'' = 5\mu$)

INTERPRETATION OF THE EXPERIMENTS

The machined hemishell is the culmination of all the engineering and metrology concepts included in the experimental apparatus and the machining process. Therefore, the geometrical perfection of the finished component provides an assessment of all the engineering and metrology concepts and determines to what extent the objectives of these studies have been satisfied.

Figures 62 and 63 show the geometrical accuracies of the external surfaces. These figures also show that the major objectives of the program have been satisfied. In Figure 62, an equator-to-pole-to-equator plot profile falls within the acceptable envelope. Since the center of an imperfect shape is not clearly definable, this same profile could be replotted around a different center. For example, if the profile were moved about 15 microinches toward the pole along the polar axis, a plot for the new center would indicate a more favorable profile to work with when machining the interior surface. Adjustments of this type are certainly in keeping with the objectives of the program. In Figure 63 a plot of the equatorial profile is shown, which also falls within the acceptable envelope. The maximum deviation from idealized geometry at the equator is approximately six microinches.

Referring again to Figure 62, it is seen that an eight-microinch depression in the spherical surface exists at about the 30-degree latitude. This depression is opposite the point where the wax film secured the hemishell to the holding fixture. It is concluded that the depression is the result of the differences in thermal expansion behavior of the wax, hemishell, and holding fixture. This condition, although undesirable, does not defeat the objectives of the program. To correct this condition, the thickness of the wax film must be decreased or another holding substance selected that has a lower thermal expansion coefficient.

The average diameter of the hemishell shown in Figure 62 is about eight microinches less than the nominal diameter even though the average diameter measured while this piece was still mounted in the holding fixture was about five microinches greater than the nominal diameter. This difference may be explained by a temperature difference which exists between the machining and measuring operations. The measuring was done with the hemishells removed from the holding fixture. A difference of 0.2° F would account for this disagreement. The hemishells, as plotted, were measured at 8 am when the temperature of the laboratory was approximately 0.2° F less than the standard condition of 68.0° F.

Roundness measurements (equator or equator-to-pole-to-equator measurements) fall within the accepted tolerance envelope and verify the rotational and thrust accuracies of both the work and cutterhead spindles under dynamic conditions.

Correlation of the geometrical data implies that the metrology concepts were valid. However, experiments associated with the turning of the interior surfaces were not completed because of the time limitations in the subcontract. It is believed that the results of the interior surface turning would be as satisfying as those of the exterior surface turning.

An important consideration in the Phase II studies is the effect of temperature control on geometry. As previously pointed out, a major objective is to maintain a precise temperature control, a critical factor in achieving the required geometrical accuracies by meticulous attention to all heat sources. The fact that these accuracies were achieved without having to make special corrections or compensations for thermal effects attests to the soundness and validity of the temperature-control concepts applied in this study.

CONCLUSIONS

The following conclusions can be stated as a result of this study:

1. The effects of the temperature gradients encountered in the earlier machining studies and the resulting difficulties imparted to the machining measuring processes were practically eliminated through use of temperature-controlled cooling systems. As a result, the precise machining and measuring processes were performed without undue concern for thermal distortions.
2. Thermal gradients present in either the hemishell or holding fixture during the mounting process result in strains which frustrate microinch control during machining.
3. Holding fixtures must be made of materials having the same coefficient of thermal expansion as the workpiece.
4. To achieve optimum dimensional control in any ultraprecision machining system, it is essential that the entire system be analyzed to minimize, isolate, and dissipate all heat sources.
5. Metrology systems based on white-light interferometry are required to provide the versatility and accuracy necessary for machining to microinch tolerances.

RECOMMENDATIONS

The following recommendations are made as a result of this study:

1. All gas bearings in the hemishell turning machine should be replaced with bearings possessing characteristics approaching the curves shown in Figures 64 and 65. This modification would minimize the deflections of both spindles.

Figure 64. GAS FILM THICKNESS AS A FUNCTION OF THE AVERAGE UNIT PRESSURE IN THE FILM. (Supply at 100 psig; 1/16" D Holes)

Figure 65. GAS CONSUMPTION AS A FUNCTION OF THE FILM THICKNESS. (2" x 4" Flat Experimental Air Shoe - Graphitar Type 80 - Nitrogen Gas Supply)

2. Consideration should be given to replacing the radial bearing seats (Item 1038-E, Figure 51) with spherical-type seats used in Phase I (Figure 4, Item 104-D). Improved spindle stiffness should result from this change.
3. The journal-bearing shoes of the cutterhead spindle are joined through a flexure. It is suggested that the flexure be removed, thus allowing for self alignment of each shoe without interference from adjoining shoes. (Orientation of the work spindle precludes any advantage by removing the flexures in this unit.)
4. Amounting wax should be sought having the same or nearly the same coefficient of thermal expansion as the workpiece and holding fixture.

EXHIBIT A

TEMPERATURE CONTROL IN THE HEMISHELL TURNING MACHINE

Temperature control of the machining system was achieved by circulating a liquid through the critical parts. The ideal liquid possesses a very large specific heat value, is an excellent heat conductor, and has low viscosity. Water was chosen on the basis of these criteria.

Figure 50 is a schematic drawing of the heat dissipation system in the hemishell turning machine. Two constant-temperature baths are shown with four pumps to transfer water from the baths to the critical parts of the machine. The manufacturer's claims state that these baths will maintain a constant temperature, relative to the set point, of $\pm 0.05^{\circ}\text{F}$.

Bath 1 has a 38 Btu/min capacity^(u) while Bath 2 has a 57 Btu/min capacity. The total capacity appears to be more than sufficient for the purpose. Four pumps deliver about 9 gpm or 75 lbs of water/min to the apparatus. With a 0.2°F temperature rise in the circulating water, 15 Btus/min could be dissipated. Table 2 itemizes the estimated head load of 8.2 Btus/min contributed by the apparatus to the constant-temperature baths. In addition, the baths dissipate heat developed by pumping and agitation. This heat load was never measured.

Table 2 is a guide (but not a true assessment) for sizing the water circulation system. The original plan was to measure the flow rates and temperature rise of the water at critical points within the system. Thus, more exact data indicating the heat energy relative to the various parts of the machining process and the mechanism would be developed. It is assumed that the system could be optimized from these data, thus providing a more precise temperature control of the machining process. However, because of the expiration date of the subcontract, none of these refinements were made.

With reference to Figure 50 (showing the cavity within the main casting, Item MR-1029), the circulation pattern of the water is indicated. Liquid is supplied to the inlet nozzle (1/2" D) by the Jabsco B-6, M6-V pump at 5.6 gpm. These conditions produce a discharge velocity of about 9 ft/sec. Temperature gradients measured throughout the main casting indicated that this discharge velocity was adequate to maintain the desired temperature control.

(u) This value was obtained by the extrapolation of the load curve supplied by the manufacturer.

Table 2
ESTIMATE OF THE HEAT LOAD CONTRIBUTED BY THE
HEMISHELL TURNING MACHINE TO THE
TEMPERATURE-CONTROLLING BATHS

Item	Heat Generated (Btus/min)
Work Spindle	2.7
Work Spindle Drive Motor	1.4
Cutterhead Spindle Drive Motor	0.1 ⁽¹⁾
Operating Personnel	1.4 ⁽¹⁾
Metal Removal Process	2.6 ⁽¹⁾
Total	8.2

(1) Developed from experiences with the hemisphere turning machine.

Eight thermometers, readable to 0.1°F , were located around the casting. Several tests were run to evaluate the temperature gradients. No readable temperature gradient was observed when the work spindle turned at 2,000 rpm without machining. However, with work in process, two thermometers in the vicinity of the work spindle on the operator's side showed a temperature rise about 0.1°F . Elevation in temperature was believed caused by the operator (an average human being radiates heat equivalent to a 100-watt source) since the thermometers on the opposite side of the casting showed no change.

Figure 66 is a photograph of the two constant-temperature baths located in a room adjacent to the laboratory. Each bath consumes more than 1,000 watts of electrical energy for refrigeration and heating. To provide optimum environmental temperature conditions for the hemishell turning machine, the baths were located outside the laboratory. Although longer pipe lines were required to transport water, the compromise was worthwhile.

The 5.6-gpm pump was connected by $3/4$ -inch-ID tubing; all others were connected with $1/2$ -inch-ID tubing. Oversized piping connections minimized the temperature rise caused from a high pumping pressure. To further maintain the temperature of the liquid, all lines (Figures 47, 48, and 66) were covered with a foam-rubber thermal insulator. The temperature rise during transport from bath to apparatus was 0.1 to 0.2°F . With these factors in mind, the set-point temperature for both baths was 67.8°F . Thus, the temperature of the apparatus could vary from 67.9 to 68.1°F with respect to the intended operating temperature range.

Evaluation of the Temperature Controlling System

This system was evaluated with respect to the overall performance of the machine tool. The following conditions show how well the system met its intended function:

Figure 66. CONSTANT TEMPERATURE BATHS.

1. Using an interferometer, axial drift of the work spindle was measured at 15-minute intervals over a 4-hour period. During this time, the reference surface, a gage block wrung on the noze of the work spindle, varied from the set position a maximum of 0.10 microinch. Three tests gave results with the same general trend. The axial reference would initially move in a plus direction, reaching about 10 microinches within the first hour, and then in the reverse direction, reaching a maximum in the opposite direction of approximately 10 microinches minus the initial set point. After 4 hours, the reference reached a position about 5 microinches minus the initial set point.
2. Hemishells were turned without temperature-compensating adjustments. The accuracy achieved supports the experimental concepts.

EXHIBIT B

DESIGN OF THE HYDROSTATIC GAS BEARING AND SPINDLE

Gas Bearings

In the machine built under Phase I of this effort, the thrust bearings were located at the opposite ends of the spindle assembly some 17.5 inches apart. Consequently, any temperature change within the rotating shaft has a pronounced effect on the axial position of the work (see Page 43).

An objective of the current study was to minimize this type of dimensional instability. Two modifications to the spindle design were made to achieve axial stability: (1) the distance between the thrust faces of the bearings was minimized, and (2) provisions were made to dissipate the heat developed in the gas lubricating film to avoid upsetting the temperature equilibrium of the apparatus.

The design used to satisfy the axial stability requirement is shown in Figure 51. The distance between the thrust faces of the bearings (Item 1039-A) is 1.25 inches in contrast to the 17.5 inches used in the older design. The main structural element (Item 1037-A, Figure 52) of this bearing assembly is machined with 72 symmetrically special radial passages for the circulation of a heat-dissipating liquid.

The porous element of the thrust bearing, noted as "Graphitar G-2" (Detail MR-1039-A, Figure 67), is shown cemented to the stainless steel backup plate. This drawing also shows 233, 1/16-inch-diameter drilled holes through the backup plate. It will be noted that the overall thickness of the composite is 0.197 inch. This structure is equivalent to the 0.500 inch thickness of Graphitar G-2 used in the thrust bearings of the hemisphere turning machine. Another important feature of this design is the positioning of the 72 radially drilled passages close to the gas lubricating film thereby improving heat dissipation from the film. A second advantage of the new design is the ability to compensate for changes in the Graphitar porosity by changing the size of the drilled holes.

The design procedure for the journal and thrust bearings is identical to that discussed under Phase I (Pages 10 through 16) except that a lower supply pressure curve (100 psig) is used and the design point for film thickness is 200 instead of 100 microinches. The data used are depicted by the curve shown in Figure 64, which was developed from a 2-inch by 4-inch experimental gas bearing having a composite structure identical to that described in the previous paragraph. The choice of a greater film thickness and a lower supply pressure curve resulted from experience gained in the Phase I studies. This experience led to the following conclusions:

Figure 67. HEMISHELL TURNING MACHINE SPINDLE DETAILS.

1. Gas film stiffness was compromised by selecting a lower supply pressure. This compromise was offset, however, by the lower gas consumption at the lower supply pressure.
2. A thicker gas film develops far less heat. This change resulted in an appreciable improvement in thermal stability.

Gas consumption for the new bearing design is indicated by the graph of Figure 65. This curve rises more rapidly than the curve for the older design, indicating a greater gas consumption, especially with thicker films, when using the new design. However, the increase is not excessive. The additional gas consumption is a fair price to pay for the advantage of better heat dissipation in the work-spindle thrust bearing.

Spindle

Efforts to make the rotating elements of the cutterhead spindle and work spindle of a one-piece design were unsuccessful because a concept compatible with ultra-precise fabrication techniques could not be developed. Hence, it was necessary to develop the two-piece work-spindle design shown in Figure 51, as Items 1036-A and 1038-A. (The cutterhead spindle design is similar.)

Attention is called to the location of the nut, Item 1038-C, at the rear of the spindle where fastening strains will have a minimum effect. The fastening strains elsewhere in the assembly occur at accurately lapped surfaces producing symmetrical strain about the spindle axis, thereby having a minimum effect on the rotating accuracy of the component. The fitup of these two parts is discussed in Exhibit D.

The two-piece construction complicates any prediction of the deflection resulting from machining loads. While stiffness was sacrificed somewhat, it was more than offset by improved temperature control and axial stability.

The calculated deflections for both spindles are given in Table 3. These values were developed by the procedures described under Phase I (Pages 16 through 21). Figures 68 and 69 show the models representing the imposed loads on the spindles when machining the largest-sized workpiece, namely, an 8-inch-diameter sphere.

Test Thrust Bearing

An experimental thrust bearing incorporating all of the new ideas was made and tested under operating conditions during the turning of hard materials. (This was done by replacing Parts 101-C and 102-D, Figure 4, Page 17.) Test data showed the deflection rate to be 0.5 μ in/lb. The new bearing had a slightly greater deflection rate, but it also consumed less gas.

Table 3
CALCULATED RADIAL DISPLACEMENT AT THE TOOL POSITION

	Deflection as a Free Beam (μin)	Deflection as a Guided Beam (μin)	Deflection in Gas Film (μin)	Maximum Deflection (μin)	Minimum Deflection (μin)
Cutterhead Spindle	2.6	0.016	0.68	3.28	0.7
Work Spindle	2.2	0.016	0.60	2.8	0.62

Figure 68. BENDING OF THE WORK SPINDLE.

(a) Case 1, Free Beam

(b) Case 2, One End Guided

Figure 69. BENDING OF THE CUTTERHEAD SPINDLE.

Discrepancies between the test bearing, from which the curves were developed, and the thrust bearing arises from the variation in permeability or porosity of the sintered graphite bearing element. The supplier has been contacted on several occasions with requests for more uniform material, but it is doubtful if present manufacturing controls are capable of meeting the required specification for precisely uniform porosity.

Bearing Performance

When the bearings for the hemishell turning machine were fabricated and tested, about one half of the sintered graphite elements showed a permeability or porosity greater than any previously observed. The gas consumption of the poorest of these

bearings was about six times greater than predicted from the curve shown in Figure 65. Poorer elements were discarded and replaced; the better bearings were selected for use in the work spindle, while some marginal ones were used in the cutterhead spindle assembly. Being uncertain of the degree to which compromises could be made, this procedure was followed to prevent a serious delay in the work schedule.

Spindle Performance

The accuracy of both spindles was well within the design limits. Runout and axial deviation were less than two microinches under static conditions. Dynamically, the work spindle performed very well. Dynamic conditions for the cutterhead spindle were felt to be unimportant and not determined.

Static deflection tests were made in accordance with the models (Figures 68 and 69). The work spindle showed a thrust stiffness of $1.0 \mu\text{in/lb}$ and a radial stiffness of $5 \mu\text{in/lb}$; the cutterhead spindle showed a thrust stiffness of $1.25 \mu\text{in/lb}$ and a radial stiffness of $8.0 \mu\text{in/lb}$. The radial stiffness for both spindles was less than the predicted values of Table 3 by a factor of approximately two. The thrust stiffness was less than the calculated values by a factor of five.

The lack of stiffness in the spindles is attributed to: (1) excess porosity (permeability) in the Graphitar, and (2) loss of beam stiffness because of the two-part construction of the rotating element. It is felt that the equipment would test within the design limits set by Table 3 if the bearings were rebuilt with a Graphitar element possessing the characteristics indicated by the curve of Figure 64.

EXHIBIT C

LAPPING AND MEASURING EQUIPMENT FOR SPINDLES

The rotating element in the cutterhead spindle and work spindle is of a two-part construction requiring very accurate registration between the two parts when assembled. This requirement is obvious when studying the arrangement of Drawing MR-109 (Figure 51), which shows the two components and the guiding surfaces which comprise parts of the gas bearings. To assure proper registration of the two critical components, special laps and diameter measuring equipment were designed and built in accordance with Arrangement Drawing MRX-1025 (Figure 70).

The lapping equipment is suitable for finishing the inside and outside-diameter registering surfaces of the spindle components. The objective of the particular lap design is twofold:

1. To finish the registering surfaces of the spindles with a 50-microinch interference when assembled.
2. To make these lapped spindle surfaces coincident with a common axis.

The male and female components are placed one within the other to produce finely lapped, true surfaces. The trueness of these laps is inherent and is imparted to the spindle component.

The interferometers shown in Figure 70 are used to reference the spindle diameter to the gage-block size using white-light interferometry. Deviation from the gage-block size is determined by fringe reading.

Processing of the journal and thrust bearing surfaces is identical to that described under Phase I (Pages 29 through 34).

EXHIBIT D

ASSEMBLY OF SPINDLES

The geometrical accuracies of the assembly should equal the accuracy of the two parts of the rotating element (Figure 51, Items 1038-A and 1036-A for the work spindle; Items 1038-F and 1041-A for the cutterhead spindle). The assemblies are shown in Figure 51. Experience during the initial assembly efforts showed that much of the original accuracy was lost when assembled. Most of the difficulties were attributed to:

1. Scoring of the registering surfaces during assembly (although slight).
2. Variation in the film thickness of the lubricant applied to the registering surfaces even though the film application was as thin as possible.
3. Inability to maintain clearance between the registering surfaces during the shrink-fitting assembly process. Thermal gradients could not be controlled for a time sufficient to achieve the required geometrical relationship between the two parts. The consequence was an interference fit with nonsymmetrical strains causing the guiding surfaces to deviate from a true geometry.

These difficulties were minimized by changing the assembly as follows:

1. The interference fits were reduced from 200 to 50 microinches.
2. The two components were assembled by a method that was independent of the time for maintaining clearance between the registering surfaces during fitup.

An alternate method was devised which included lapping and measuring the registering surfaces, as described in Exhibit C. This method also included a technique utilizing Poisson's ratio for providing clearance between the registering surfaces during fitup that was independent of time and eliminated the troublesome thermal gradients. In general, this concept requires that a longitudinal strain in a shaft be accompanied by a transverse strain. Poisson's ratio for steel transverse strain/longitudinal strain = 0.33. Details of this concept are covered in most mechanical engineering handbooks.

Figure 71 shows the application of the technique using Poisson's ratio. The inner member of the two-part shaft assembly is attached at one end to the H-beam frame; the opposite end is attached through one adapter and a rod to a hydraulic jack capable of exerting a 30-ton tension force on the inner shaft (Item 1036-A). Under the resulting strain, the three-inch-diameter upper registering surface reduces a calculated 275 microinches in diameter, while the lower 3.375-inch-diameter registering surface reduces 240 microinches.

Figure 71. HYDRAULIC TENSIONER FOR THE SPINDLE ASSEMBLY.

In practice, the upper registering surface adhered to the calculated values, while the lower was substantially less. The lower surface was very close to the bulky spindle nose, and the transverse strain was frustrated, to some extent. Even so, there was sufficient reduction in diameter to fit the outer sleeve (Item 1038-A) over the inner shaft (Item 1036-A).

EXHIBIT E

SPINDLE ALIGNMENT

Precise spindle alignment is mandatory to achieve the geometrical machining accuracies set forth in the objectives of these studies. Deviation from the ideal more than a very few microinches defeats the purpose. The spindles are properly aligned when the following conditions are met:

1. The axis of rotation of the work spindle must be parallel to the transverse motion of the carriage within five microinches measured within the two to five inches that exist between the cutterhead spindle rotational axis and the work-spindle nose.
2. The rotational axes of the work and cutterhead spindles must intersect within five microinches.
3. The rotational axes must intersect at 90 ± 1 degrees.

Spindle alignment is a two-step process. In Step 1, the spindles are aligned to conventional dimensional tolerances using mechanical dial indicators and micrometers; in Step 2, the process is repeated using interferometer measuring systems to evaluate the accuracy of alignment. The procedures for assembly and for gas-bearing adjustment are practically identical to those described in Phase I (Pages 34 and 35).

The alignment of the work spindle begins immediately after the spindle floats on a gas film in the radial bearings. A 1/4-inch-diameter steel rod, threaded on each end, is inserted through the central hole in the spindle. The rod is about three inches longer than the spindle. A nut and washer are applied at the nose end. A 1/2 by 2 by 10-inch-long steel piece is provided with a 5/16-inch hole drilled through the geometrical center of the 2 by 10-inch surface. The 5/16-inch hole is inserted over the 1/4-inch rod at the drive sheave end. The ends of the steel piece are blocked between the faces of the main casting (Item 1029, Figure 51). A nut and washer are applied and tightened urging the thrust bearing (Item 1037-A, Figure 51) against its seat. This procedure seats the thrust bearing against the tapered seat in the main casting without any misaligning moments. The clamping ring (Item 1037-B, Figure 51) is applied using eight Size 10 buttonhead cap screws evenly tightened with a torque wrench to prevent the possibility of seating the thrust bearing inaccurately. The 1/4-inch rod, steel piece, and other items are removed.

A rotameter having a 2-scfm capacity at 100 psig is inserted into the supply line for each radial bearing. During the subsequent adjustments, each bearing must be positioned with proper clearance. In this case, proper clearance is ascertained by gas consumption. At 100 psig, each radial bearing consumes 0.6 scfm. Two small

dial indicators, such as the Last Word, (v) are secured to the spindle in a position normally occupied by the sheave. One indicator scans the plane face of the main casting (Item 1029, Figure 51); the other scans the bore in the main casting.

There are six differential screw adjustments (Item 1038-D, Figure 51), three on each radial bearing, which control the bearing adjustment for housing clearance and position. These adjustments are maneuvered until both dial indicators read within ± 200 microinches. (The surfaces scanned by the indicators are machined for rough alignment.) Additional adjustments of the thrust bearing may be made with the clamping ring (Item 1037-B), if necessary, but air consumption of each radial bearing must be maintained at 0.6 scfm at 100 psig, after adjustments are made.

The same procedure applies for the cutterhead spindle alignment with the following exception: The dial indicators are mounted at the top end of the spindle—one scanning the top surface of the carriage (Item 1032-A); the other scanning the cylindrical projection near the clamping ring (Item 1037-B) for the thrust bearing on the vertical spindle. In this case, gravity forces urge the thrust bearing (Item 1040-A) against the spherical seat so the 1/4-inch rod assembly is not used for aligning this spindle. The rotameters are inserted in the gas supply lines. For the cutterhead radial bearings, the correct consumption is 0.8 scfm at 80 psig. As with the work spindle, the radial bearings are controlled with six differential screws, three for each bearing. Adjustments are made until both indicators read within ± 200 microinches, and at the same time the gas consumption is 0.8 scfm.

After assembly, the work spindle and drive is dynamically balanced at 2,000 rpm using one of the outside-diameter measuring interferometers as was done on the work spindle of the hemisphere turning machine (Phase I, Pages 35 through 40).

The machine is now ready for the final alignment of the work spindle. Refer to the schematic drawing (Figure 72) for this operation. Preparation for these procedures requires the mounting of the outside-diameter cutterhead interferometer (Figure 56) and the test bar (Figure 73). The test bar is secured to the nose of the work spindle using Size 10 cap screws so that it is concentric with the axis of rotation to within 200 microinches TIR as measured near the mounting flange. A tungsten carbide cutting tool is mounted in the outside-diameter cutterhead interferometer. A truing cut is made over the 4 1/4-inch-diameter surface of the test bar using the manual feeding mechanism. The carbide tool is replaced with a 0.7-inch-radius diamond tool, and a second pass about 200 to 400 microinches deep is made over the previously machined 4 1/4-inch-diameter surface. Oil coolant is used to dissipate the heat developed in the test bar during these operations.

(v) Manufactured by the Starrett Company.

Figure 72. ALIGNMENT OF THE SPINDLES.

The diamond tool is replaced with a 0.7-inch-radius diamond knife, then a third cut is made over the 4 1/4-inch-diameter surface, with coolant, to a depth of about 50 microinches. During the 50-microinch cut, the spindle speed is set to approximately 800 rpm to minimize the effects of any unbalance that may be present in the test bar. The feed rate is about 0.001 inch/revolution.

The cylinder is measured for taper with outside-diameter micrometers. The amount and deviation of the taper indicates the degree of misalignment between the rotational axis of the work spindle and the motion of the carriage. The indicators and rotameters, used for spindle alignment, are reinstalled, the clamp on the thrust bearing is loosened, and the radial gas bearings are readjusted to bring the work-spindle axis parallel to the motion of the carriage.

The taper may be determined from the diameter measurements of the test bar. The amount of deviation for perfect alignment is also known when scanning the test bar from end to end with an indicator. Suppose the diameter near the spindle nose is 400 microinches larger than the cantilevered end, then scanning along the top or bottom of the test bar should show a 200-microinch parallel misalignment between the spindle axis and carriage motion. During these adjustments, the proper gas film thickness and central location within the spindle housing must be maintained. Once the adjustments are satisfactory, the 1/4-inch rod assembly is used for reseating the thrust bearing. Using a coolant, 50-microinch cuts are now made until a true diameter exists. The arrangement, shown on Figure 72, is used to determine the amount of taper by taking diameter measurements with the outside-diameter interferometers.

When the roughing alignment has been completed, fringes should persist when the cylindrical surface of the test bar is scanned from end to end using a white-light interferometer. Data from this point on are measured in terms of microinches. All of the previously discussed work-spindle adjustments were made to set the axis of rotation parallel to the carriage movement to within five microinches. A slight taper in the test bar can be compensated for without compromising the accuracy of this alignment.

EXHIBIT F

FLATNESS MEASUREMENTS OF THE SURFACES OF THE V WAYS

The carriage which consists of a main structural element (Item 1032-A, Figure 49) houses the cutterhead spindle. The guiding surfaces of the V ways on which the carriage rests must be true planes. The degree of trueness determines the ultimate accuracy of the intersection of the rotational axis of the work spindle and cutter-head spindle, a most critical requirement of the experiments. Figure 74 represents these surfaces acting as optical surfaces in a Twyman-Green interferometer system.

Figure 74. INTERFEROMETER SYSTEM USED TO MEASURE THE FLATNESS OF V-WAY SURFACES.

Before assembling on the V way, the interferometer system is assembled in its simplest form on a large granite surface plate to determine the straightness of the fringe system. The optical components produce straight fringes deviating from perfection no more than one microinch.

The Twyman-Green system is attached to the main casting (Item 1029, Figure 49) where one of the four V-way surfaces is a part of the optical system, as shown in Figure 74. The interferometer is adjusted to yield four or five fringes running lengthwise along the plane surface. If the plane is true, the fringes will be straight lines; if not, they will take some form other than a straight line. The fringes are read exactly as under an optical flat.

The plane is lapped by conventional methods to produce a true planar condition. Removal of the interferometer system is not required while lapping. This arrangement makes the measuring system quite convenient. After each lapping operation, the surface is cleaned and viewed for fringe interpretation of flatness. Any surface other than planar produces a change in the wave-front shape causing a change in fringe straightness.

To determine the accuracy of the flatness or straightness, it is necessary to analyze the system at hand. Figure 75 presents a diagram showing the interferometer leg comprising a surface of the V way.

Figure 75. CHANGE IN THE OPTICAL PATH VERSUS THE DEVIATION OF THE V-WAY SURFACE.

The nomenclature involved is:

- m which represents some integer (number of interference fringes),
- λ the wavelength of light,
- L_0 the optical path at the initial position,
- L_1 the optical path after displacement from the initial position,

d or $\frac{\lambda}{2}$ the displacement, and

θ the grazing angle of the collimated beam with the surface.

From the diagram, the following equations may be written:

$$L_0 = 2 \left(a + \frac{d}{\sin \theta} + b \right), \quad (1)$$

$$L_1 = 2 \left(a + \frac{d \cos 2\theta}{\sin \theta} + b \right), \quad (2)$$

$$\Delta L = L_0 - L_1 = 2 \left(a + \frac{d}{\sin \theta} + b \right) - 2 \left(a + \frac{d \cos 2\theta}{\sin \theta} + b \right), \text{ and} \quad (3)$$

$$m\lambda = \Delta L. \quad (4)$$

These reduce to:

$$m\lambda = \frac{2d}{\sin \theta} (1 - \cos 2\theta). \quad (5)$$

Substituting $\frac{\lambda}{2}$ for d , Equation 5 further reduces to:

$$m = 2 \sin \theta.$$

In this case, the green line of a mercury vapor light source (5461-A) was used, $\lambda = 21.5 \mu\text{in}$. Under the usual instances where the reflecting end mirror is normal to the incident beam, the displacement, d , equals $\lambda/2$ for one interference fringe displacement. Here, the grazing angle is 90 degrees. In most cases, texts dealing with interferometer systems ignore this fact; and, therefore, the expression " $\sin \theta$ " is omitted because the sine of 90 degrees equals 1. But, in this case, the grazing angle was about 9.5 degrees (θ). So, if in the process of measuring a fringe, displacement were considered equal to $\lambda/2$, or 10.75 microinches, there would be a serious measurement error.

Thus, for this case:

$$\begin{aligned} m &= 2 \sin \theta, \\ &= 2 \sin 9.5^\circ \approx 2 \times 0.167 = 0.33. \end{aligned}$$

This result merely says that the displacement of the V-way surface produced 0.33 times as much interference fringe shift. Stated another way, deviation must be three times greater to produce one fringe displacement in the viewing telescope.

So, one fringe displacement equals $3\lambda/2 = 3 \times 21.5/2 = 32.75 \text{ } \mu\text{in.}$ The fringe system was easily readable to one-fifth fringe spacing so it is possible to evaluate straightness to an accuracy of about six microinches.

For example, if the diameter of the test bar is five red fringes larger near the spindle nose, then correct alignment can be achieved by adjusting to obtain a $2 \frac{1}{2}$ -fringe shift (red) in the outside-diameter cutterhead interferometer when scanning from the end of the cylinder. It is not necessary to do any further machining on the cylindrical surfaces to make further alignment adjustments. This provision is true because the variation in cylinder diameter is now within the measuring range of all interferometers, and it will serve its purpose in the alignment procedure by acting as a known base reference.

Caution must be applied throughout the adjustment procedures to maintain proper temperature control, otherwise the precise alignment will not be achieved. The complete temperature control system (heat shield, main casting, work-spindle thrust bearing, and base casting) must be in operation throughout these procedures.

Assuming the test bar is turned to a taper of five red fringes, then the work spindle is properly aligned when:

1. The outside-diameter cutterhead interferometer reads $\pm 2 \frac{1}{2}$ red fringes when scanning the test bar from end to end along the side.
2. The outside-diameter cutterhead interferometer reads $\pm 2 \frac{1}{2}$ red fringes when scanning the test bar from end to end along a line at top dead center. Since this measurement cannot be made with the existing interferometers, an electronic displacement indicator was used to scan for a 30-microinch ($2 \frac{1}{2}$ -red fringe) reading.
3. The radial gas bearings consume 0.6 scfm of gas (air or nitrogen) at 100 psig.

Additional alignment of the spindles is accomplished by setting the cutterhead spindle axis to precisely intercept at an angle of 90 degrees to the axis of the work spindle. The cap screws on the thrust bearing clamp ring are loosened to free the thrust bearing in the cutterhead spindle. The rotameters are inserted in the gas supply lines to the radial bearings of the cutterhead spindle. The outside-diameter cutterhead interferometer is removed from the cutterhead spindle.

The cutterhead spindle must be adjusted so that its axis of rotation is 90 degrees to the axis of rotation of the work spindle. An electronic displacement indicator is mounted on the cutterhead to pass under the test bar. The carriage is moved until the axis of rotation bisects the length of the test bar. The electronic indicator sweeps under the cylindrical surface as the cutterhead spindle is rotated. The indicator is located such that the stylus of the indicator contacts the cylinder at

two positions while making a complete revolution. The difference in indicator reading between the two contacting points should be proportional to the taper over the cylinder for the distance between the two points. The differential adjusting screw on the lower radial bearing is adjusted as the stylus sweeps past the cylindrical surface so that the difference in the electronic indicator readings is commensurate with the established taper of the test piece. Gas-flow consumption must be maintained at 0.8 scfm at 80 psig for each radial bearing after these adjustments.

As previously stated, the axis of rotation of the cutterhead must intersect the axis of rotation of the work spindle to within five microinches. The carriage is moved to a position where the rotational axis of the cutterhead spindle is about 1/8 inch inside the end of the test bar. The electronic indicator is remounted with the stylus making contact with the cylindrical surface at the point of tangency of a vertical plane. Under these circumstances, the stylus can be swung around the open end of the cylinder making contact with the cylinder at positions 180 degrees apart as the cutterhead is rotated. When the cutterhead is rotated and the stylus makes contact with the edge, the reading will probably go off scale of the instrument. The cutterhead is rotated 180 degrees with the stylus going around the free end of the cylinder until a minimum reading is observed and noted. The objective now is to shift the spindle laterally, that is at right angles to the centerline of the work spindle, as viewed in Figure 72, so that the minimum readings are equal on both sides of the test bar. This shift should create minimum disturbance to the 90-degree relationship of the spindle axes. This goal can be partly, if not completely, achieved by ignoring the radial-bearing adjusting screws lying in a plane common to the two spindle axes, which means that only two of the three adjustments on each radial bearing may be used.

When optimum centering is achieved, the electronic indicator is removed from the cutterhead spindle, and the outside diameter cutterhead interferometer is remounted without a cutting tool. With the cutterhead spindle axis about 1/8 inch inside the end of the test bar, white-light fringes are sought on the cylindrical surface of the test bar through the microscope. The interferometer is set at zero when a minimum reading is observed. The cutterhead spindle is then rotated 180 degrees around the free end of the test bar. Again, the fringes are observed for a minimum reading. By noting the minimum readings at each of the 180-degree positions on the test bar, the offset of the axes can be determined. A difference of two red fringes observed at the operator position indicates that the proper radial bearing differential screws must be adjusted to shift the cutter-spindle axis to compensate for the offset by moving the spindle laterally one red fringe. The thrust bearing is secured by giving an equal tightening to the eight Size 10 cap screws, on the clamping ring, with a torque wrench. A final check is made to verify the entire alignment objective as follows:

1. Gas consumption in each radial bearing of the cutterhead spindle is 0.8 scfm at 80 psig, and gas consumption in each radial bearing of the work spindle is 0.6 scfm at 100 psig.

2. The difference in fringe reading through the interferometer is five microinches or less when the cutterhead spindle is rotated to two positions 180 degrees apart on the free end of the test bar.
3. For the conditions assumed in this description, the fringes in the interferometer will shift by $2 \frac{1}{2}$ red fringes when the carriage is moved from end to end along the test bar. When moved along the bar on a line 180 degrees from the line, the interferometer will still produce a shift of $2 \frac{1}{2}$ red fringes.
4. The outside-diameter cutterhead interferometer is removed and the electronic displacement indicator is mounted on the cutterhead spindle to scan the underside of the test bar by rotating the cutterhead spindle. Contact is made by the stylus at each end of the turned surface. The taper previously established for the test bar should be verified by these readings.

If all four of these conditions are observed, both spindles will be properly aligned.

EXHIBIT G

TWIST AND PARALLEL MEASUREMENTS OF THE V WAYS

In Exhibit F, a description is given of the flatness measurements of the plane surfaces that comprise the V ways. Flatness, or straightness, measurements in themselves are not sufficient to satisfy the needs of these studies. Also important is the orientation of the V ways to one another. Each V way is considered as a line which is the intersection of the two planes that comprise the V ways. These two lines must lie in a common plane (no twist), and they must be equidistant (parallel). Twist, parallelism, and straightness must be controlled to maintain the intersection of the axes of the two spindles.

During these tests or measurements, the main casting containing the V ways is mounted on a large granite surface plate. A measuring system was devised to accurately assess the twist and parallelism of the V ways. Figure 76 shows the arrangement systems and the details of the mechanical components. For both of these measurements, the V-way surfaces are observed through a gas lubricating film in the same way that the carriage, which rides on these ways, looks at them. Observation through a gas film produces more accurate measurements.

For parallel measurements, a white-light interferometer looks through a hole in the flexure to a mirror attached to a mechanical component housing the V-shaped gas bearing. The equipment is designed so that there will be zero displacement between the mirror and the interferometer when the V ways are scanned from end to end, if they are parallel. If the V ways are not parallel, the fringes will drift across the optical field. The amount of nonparallelism is recorded during this test. The data will be used in conjunction with the twist measurement subsequently described.

Again referring to Figure 76, the drawing shows the equipment reassembled to perform the twist measurement. The interferometer has been moved from its end position on the beam to the center of the beam looking downward. A void between the V ways exposes the surface of the granite surface plate. A stack of gage blocks of convenient height are set on the granite surface opposite the interferometer. The interferometer is positioned to produce the zero-order interference fringe (black in appearance). As with the parallel test, the system looks at the V ways through a gas lubricating film. The V ways, not shown in the plan view, run lengthwise from top to bottom of the drawing. The H beam and the entire system is turned 90 degrees about the center of the interferometer. The end of the gage block is still within view of the interferometer. If the zero-order fringe is still in its same relative position, the V ways have no twist. A shift of the zero-order fringe indicates twist is prevalent. The amount and direction of shift provide data which assess the direction and the extent of twist.

Figure 76. V-WAY PARALLELISM AND TWIST MEASUREMENT INSTRUMENTATION.

Geometrical deviations are schematically indicated in Figure 77. The value of x_1 is derived from the parallelism measurement, the concepts being indicated in the plan view; y_1 is derived from the twist measurement, the concepts being indicated in the elevation view. The angle, θ , is determined by the shape of the V cross section, in this case, a 45-degree right triangle. The control positions in the figure are arbitrarily selected. In this case they were 18 inches apart, with the righthand position about two inches from the end of the V way.

Figure 77. CORRECTION FOR TWIST AND PARALLELISM.

In practice, the parallelism arrangement is set up and mounted at a selected control position where the interferometer is set to zero. The righthand end was chosen for this work. The whole system, suspended on a gas lubricating film, is traversed to the other control position, in this case, at the left. A measurement is made from the interferometer. A shift of one red fringe in the distance between the interferometer and the reference mirror would indicate an x_1 measurement of 12 micro-inches.

The equipment is reassembled to satisfy the twist measurement and positioned on the V ways so that one gas bearing is located at the control position near Point A and the other at the position near Point D (plan view). The length of the H beam of the system was selected to match the control positions. The interferometer observing

the gage blocks is set at zero, then the system is rotated around the centerline of the interferometer approximately 90 degrees so that the gas bearings are centered over the control position near Points C and B. A reading from the gage block showing greater distance indicates twist in the direction indicated in the schematic drawing; a reading showing a lesser distance indicates twist in the opposite direction. The shift in interference fringes indicates that one half of the twist exists between the control positions. For example, a shift of one red fringe represents approximately 12 microinches; therefore, twist in the 18 inches between control positions would be about 24 microinches, the value for y_1 .

Section AA in the lower right of Figure 77 shows rectangular coordinates set up with the origin "0" representing the intersection of a true V way (straight-line representation) and the line called "control position". Point (x_1, y_1) represents the V way measured for twist and parallelism using the other V way, AB, as a reference. The x_1 and y_1 values are the corrections needed at this position to eliminate non-parallelism and twist, respectively. To determine the amount of material to be removed at this position for correction, data at hand must be translated into another frame of reference; namely, the rectangular coordinate system represented by axes $x' - x'$ and $y' - y'$ with the origin at 0.

In the new frame of reference:

$$y'_1 = (y_1 - x_1) \sin \theta + \frac{x_1}{\sin \theta}$$

equals the thickness of material to be removed from the right side of the V-way surface at Section AA;

$$x'_1 = (y_1 - x_1) \sin \theta$$

equals the thickness of material to be removed from the left side at Section AA. For example, using the values given previously:

$$x_1 = 12 \mu\text{in},$$

$$y_1 = 24 \mu\text{in},$$

$$y'_1 = (24 - 12) 0.7 + \frac{12}{0.7} = 8.4 + 17 = 25.4 \mu\text{in}, \text{ and}$$

$$x'_1 = (24 - 12) 0.7 = 8.4 \mu\text{in},$$

then using an optical flat about four inches in diameter as a measuring device, the right side of the V-way surface at Section AA (control position near Point C) would be lapped to develop a depression about 25 microinches deep and on the left side about 8 microinches deep.

Further lapping of the V way between Points C and D develops a new plane on the right side tangent to the control position near Point D and to the localized depression near Point C. Identical lapping must be performed on the left side. These new planes would obviously be developed further to include the whole length of the CD V way. Control of the planes is achieved with the use of the flatness or straightness interferometer measuring system.

The V ways of this equipment measured twist and parallelism less than 15 microinches over 36 inches of length. The straightness of all four planes comprising the V way was less than six microinches. There is a consideration that must be made in looking at these measurements; namely, temperature gradients through the main casting did not exceed 0.1°F , as determined by surface measurements with conventional contact thermometers.

Temperature gradients are obviously critical with respect to the dimensional values measured. Regardless, the carriage tracks a straight line with negligible deviation from trueness. Variation in the air-film thickness will compensate within the range of error.

EXHIBIT H

MANUFACTURE AND ADJUSTMENT OF THE INTERFEROMETER CUBE-PRISM BEAM SPLITTER

The cube-prism beam splitter, shown in Figure 78, is the essential optical part of the white-light interferometers used in these studies. Two sizes were made to satisfy the various interferometer systems; namely, 3/16 and 1/2-inch cubes. The cubes were manufactured by grinding and polishing a relatively long three-sided prism with the cross-sectional shape shown in the upper lefthand corner of Figure 78 as one half of the end view. All prisms were manufactured to an angular tolerance of ± 5 sec of arc.

Figure 78. CUBE-PRISM BEAM SPLITTER. (Isometric Exploded View)

The long prism, 2 1/2 to 3 inches in length, was diamond-saw cut into four 1/2-inch lengths. Each 1/2-inch-long piece was match marked so that its position in

the parent piece would be known. Four individual prisms were assembled to yield two cube-prism beam splitters, as shown in Figure 78. The pieces were paired using match markings so that the 45-degree tolerance errors were symmetrical about the interface. One of each pair was vacuum coated with titanium oxide on the long face to provide a coating weight that yielded 50 percent reflection and 50 percent transmission for white light. Each of the other faces (not including the cut or end faces) was vacuum coated with magnesium fluoride to minimize back reflections from the air-to-glass surfaces. The prisms were assembled, as shown in Figure 78.

A special instrument called the Prism Adjusting Interferometer, Figures 79 and 80, was designed and built so that the prisms could be properly assembled. This instrument was required to make the fine adjustment necessary in the assembly of the prism.

Sequential steps of assembly are described as follows: A pair of prisms, with the proper match marks, are selected and the optically polished surfaces thoroughly cleaned. Each of the two prisms is optically contacted to the other along the hypotenuse to form a cube.

The assembly is then inserted in the Prism Adjusting Interferometer. (Figure 80 shows the hypotenuse interface oriented along the $y' - y$ axis.) The titanium oxide-coated part may be on the top or bottom. The end mirror adjustment units in each leg are completely removed from the instrument, the light source is adjusted so that the field is evenly illuminated, and the microscope is positioned to focus on the air-to-glass surface through the prism. Two surfaces will come into view, one looking directly through the prism, the other reflecting from the titanium oxide coating. It may be necessary to darken the room to see a good image because of the reflected light in the microscope from the air-to-glass surface (at normal incidence the reflection is about 4% of the incident intensity). Coating the air-to-glass surfaces with magnesium fluoride antireflection material reduces the intensity of the reflected light.

Adjust the light source until the pinhole image is clearly defined, then adjust the differential screw for linear movement along $y - y'$ axis, searching for white-light interference fringes. (Fringes are usually crowded.) The differential screw for angular positioning the top half of the prism, on the $x' - x$ axis, adjusts to spread the fringes. Several adjustments may be necessary to obtain good fringes which indicate zero-order interference across the field.^(w)

(w) Real zero-order interference is described as true, black fringes in a field illuminated with white light. Zero-order interference, in this case, may be described as a white fringe between two dark (red to purple) fringes.

Figure 79. PRISM ADJUSTING INTERFEROMETER.

Figure 80. PRINCIPAL COMPONENTS OF THE PRISM ADJUSTING INTERFEROMETER.

The steel end plates (Figure 78) are coated with epoxy resin and mounted on the instrument with the centering pin engaging the central hole in the plate. Both steel end plates are positioned to contact the diamond saw-cut surfaces of the prism pair by pressing the centering pins. The prism end-plate subassembly is removed from the instrument and inserted in an oven at room temperature. The oven is heated slowly to the curing temperature of the epoxy resin, the curing temperature is maintained for about 1/2 hr, then the oven is allowed to cool to room temperature. After removing the subassembly, the prism is cleaned and installed in the interferometer. This procedure must be followed for prisms destined to become a part of an interferometer system having compensating optical wedges to produce a single black fringe such as is shown in Figure 81.

For instruments without optical compensating wedges, such as the outside-diameter cutterhead interferometer (Figure 56), the cube-prism adjustment is modified as outlined in the description that follows. At the position in the preceding description noted,^(w) the following sequence is inserted: End mirrors are installed in the instrument 1/4 inch from the prism face, then the microscope is adjusted to bring the end mirrors into sharp focus. The light source must also be adjusted to produce a sharp image of the pinhole. With a slight adjustment of either end mirror, white-light fringes will appear in the field as well as two of the previously mentioned dark fringes.

Subsequent adjustment produces a single black fringe in the fringe system. With differential screws for adjustment along the $y' - y$ axis, slowly move the lower half of the prism. Simultaneously, fringes must be maintained in the center of the field by adjusting either of the end mirrors. During this adjustment, one of the two dark fringes will become darker, while the other approaches a purple color. Optimum adjustment is achieved when the darker fringe becomes truly black and the color order on each side of the black is completely symmetrical. At this point the steel end plates are applied.

EXHIBIT I

OPTICAL ALIGNMENT OF THE POINT INTERFEROMETER

Optical alignment (Figure 81) is initiated after completion of the mechanical assembly. First, the cube-prism beam splitter must be aligned angularly. To make the cube prism accessible, the light source must be removed. This disassembly is accomplished by removing four Size 4 cap screws (Items 1007-A to 1006-C). Also, the reference surface holder (Item 1006-H) is dismounted by removing two Size 4 cap screws.

Initial alignment of the prism requires orthogonal adjustment of its optical surfaces to the two optical axes, one vertical and the other horizontal with reference to the drawing. Place the partly assembled instrument on a granite surface plate resting on the ground surface of Item 1006-A. Using an electronic indicator, mounted on the surface plate, the sensing head is adjusted so that the stylus contacts the top horizontal cube prism face. By scanning the prism using the granite surface plate as a reference, information is obtained to show the direction of angular movement necessary to make the face parallel to the surface plate.

Angular adjustment about the lengthwise axis is achieved by turning two Size 4 set screws at the surface where Item 1006-H is normally mounted. Angular adjustment about an axis perpendicular to the plane of the drawing is achieved by lightly tapping on the steel end plates secured to the ends of the prism. Initial adjustment is considered satisfactory when the electronic displacement indicator shows the prism surface to be within 0.001 inch of the granite surface.

Next, a gage block is fixed against the surface normally used to mount the reference surface holder (Item 1006-H). A gaging surface thus faces the prism and is in a position to reflect light back into the prism. Rubberbands may be used to hold the gage block in place. Loosen the Size 10 set screw securing the microscope barrel, and position the eyepiece in the barrel allowing about 1/8 inch of space between the eyepiece shoulder and the end of the barrel. Then, position the whole microscope assembly to bring the gage-block surface into sharp focus. It may be necessary to illuminate the gage-block surface with a flashlight projecting its beam through the aperture normally occupied by the light source.

Retighten the Size 10 set screw. Remount the light source using four Size 4 cap screws securing Item 1007-A to 1006-C. Then, position the lens cell (Item 1006-E) along its optical axis to produce a sharp image of the pinhole viewed through the microscope. (Do not adjust the eyepiece to produce a sharp image.) Place a 90-degree angle block with one face resting on the granite surface plate and the other facing the beam projected from the interferometer. The reflecting surface of the angle block must be square to the instrument base and to one of the vertical plane

surfaces of the base within ± 20 seconds of arc. Slide the instrument through its base (Item 1006-A) until the angle-block surface comes into focus. Then the differential nut (Item 1006-D) will adjust for sharp focus.

If the pinhole image is not centered over the cross hairs in the eyepiece, the prism holder (Item 1006-G) may require movement along the horizontal axis. This adjustment positions the image high or low in the field. Generally, if the mechanical parts are manufactured to the specified tolerances, the image will be sufficiently well located laterally. A check is made of the proper orientation of the optical wedges (Item 1006-M). The manufacturer shall have indicated the thick side of the wedge with a mark. When properly oriented, the marks will be in the plane of the drawing. The location of the manufacturer's mark is of no significance.

With the differential nut (Item 1006-D), a search is made for white-light fringes. When fringes appear, they may be crowded. Adjusting the Size 4 set screws (accessible at the surface where Item 1006-H is normally mounted) will produce the maximum fringe spread. Again, remove the light source (Item 1007-A) and lightly tap the steel end plate of the prism to turn the prism slightly. The fringes will spread further in one direction. By working back and forth between the adjustments, one solid color can be produced across the field.

Remove the gage block and reinstall the reference surface in its holder (Item 1006-H). Adjust the differential nut again to produce fringes. The fringes will have the bull's-eye configuration because of the spherical shape of the reference surface. By maneuvering the reference with the clearance around the Size 4 cap screws the bull's-eye should be centered with the cross hairs; now, one very black fringe should be noticeable. If the black fringe is not apparent, further adjustment of the lower optical wedge with the Size 4 buttonhead socket cap screw, shown in the section at the lower left, must be made. When a black fringe appears, the instrument is completely adjusted.

Positioning the interferometer in the metrology system is described in the Phase I Section of this report (Pages 40 through 42).

EXHIBIT J

PHASE SHIFT IN THE WHITE-LIGHT INTERFEROMETERS

Practically all dimensional measurements throughout these studies use a white-light interferometer as a position sensor. In certain instances, comparison of surfaces of different materials is made (ie, steel vs aluminum). In metallic reflection, the reflecting surface or optical surface appears to lie a few microinches beneath the geometrical surface. This apparent difference in surfaces is the result of a phase shift in the reflected light. Comparisons of shifts in phase is an important consideration. The difference can be a measurement error if it is excessive and not compensated for. Therefore, for accurate measurement, it is mandatory that compensation be made for the difference in optical and geometrical surfaces in the aluminum work material and the steel gage-block material.

Figure 82 shows a test devised to measure the differences in phase shift between aluminum and steel. A steel gage block is coated to a thickness of approximately

Figure 82. MEASUREMENT OF PHASE SHIFT.

five microinches by vacuum deposition of aluminum on one half of its surface. The height of the step on the gaging surface is measured with a white-light interferometer and recorded. The height of the step is determined by reading fringes in a manner similar to that shown in Figure 44. The gage block is given a second vacuum deposition of aluminum about five microinches thick over the entire gage surface.

Again, the step height is measured with a white-light interferometer. Several readings were averaged and a value of 0.3 microinch was obtained as the difference in step height between the two readings. This difference resulted from the phase-shift differential between the steel and aluminum surfaces. The largest reading was obtained by comparing aluminum with steel. Since two interferometers are involved in making diameter measurements, the direct measurements of the diameter of the aluminum when compared to the steel gage block must be increased by 0.6 microinch. From a practical point of view this difference is so small that it can be ignored.

The same test was made with tungsten carbide gage blocks coated with aluminum. The observed difference in the step averaged 2.5 microinches, the greatest step height being observed when comparing aluminum with tungsten carbide. Therefore, if tungsten carbide gage blocks are used as a size reference, five microinches must be added to the aluminum spherical surface to compensate for phase shift. This difference is significant and cannot be ignored.

EXHIBIT K

MOUNTING OF HEMISHELLS WITHOUT STRESS OR STRAIN

The equipment and materials required to mount hemishells are as follows:

1. A precision temperature-controlled oven with a capacity of about 1 cu ft.
2. A small circulating fan with the motor located outside the oven. The opening of the fan drive shaft should restrict the flow of room air which may cause disturbing thermal gradients.
3. A copper enclosure comprising the following: a disc (7" D x 1/4" T), a disc (7" D x 1/2" T), and a cylindrical sleeve (6" OD x 5 1/2" ID x 7" L).
4. A two-piece aluminum parallel with a screw-thread mechanism to adjust for height (shown in Figure 59).
5. A special wax—Stickum 170.^(x)
6. A hot plate.
7. A flat-bottom pan (~ 6" x 12" x 2" deep).

The method for mounting the hemishell to the fixture (1053-A, Figure 83, modified as per Figure 60) is as follows:

1. Place the flat-bottom pan on a hot plate and fill it about 3/4 inch deep with distilled water.
2. Place the holding fixture at one end of the flat-bottom pan and the hemishell on a piece of cotton (inside diameter up) at the other end of the pan. Place a thermometer in the water.
3. Heat to about 200° F.
4. When the fixture and hemishell reach the water temperature, apply Stickum to the contacting surfaces by rubbing. A coating several mils thick should be deposited on each surface.

(x) Sold by E. M. Hanson and Company, Philadelphia, Pennsylvania.

5. Place the hemishell on the holding fixture in the approximate position.
6. Remove the fixture, with the hemishell attached, from the pan.
7. Place the aluminum parallel over the fixture.
8. Set the assembly on a surface plate with paper beneath the fixture and parallel.
9. Adjust the aluminum parallel so that a clearance of 0.002 to 0.003 inch exists all around.
10. Assemble, as shown in Figure 59, and put the assembly in an oven preheated to 230° F.
11. After one hour at 230° F, turn off the oven.
12. Allow the oven to cool to room temperature (about 12 hours). Remove the assembly.
13. Remove any excess wax from the bottom of the fixture, cap screw holes, and the exterior of the fixture with a solvent such as xylene.

The mounting procedure described is also included as Step 24, Exhibit L, which covers the features of the machining process. A similar procedure is used to mount the hemishell on the holding fixture (1053-B, Figure 83); for Step 32, Exhibit L, the major difference between these two mountings is that the aluminum parallel must have a design suitable for the upside-down attitude of the hemishell.

The mounting of the hemishell for Steps 2 and 11 of Exhibit L does not require the oven treatment.

EXHIBIT L

MACHINE PROCESS PROCEDURE

The notable difference between the machining processes used in this study and conventional processes is the degree of integration of the metrology systems. Machining and measuring are so closely related that the metrology system is an integral part of the overall machine. This philosophy is apparent in the study of the design of the machine and the description of the machining process as follows:

1. A rough-finished Type 2014 aluminum alloy hemishell (zero temper; 4.03" OD x 3.97" ID) is turned from five-inch-diameter bar on a conventional lathe. The spherical surface subtends an arc of approximately 200 degrees. The final 1/32 inch of stock is removed with a newly sharpened tungsten carbide tool with a feed rate not exceeding 0.002 inch/revolution (to minimize machining stresses).
2. The hemishell is mounted in the holding fixture (Item 1053-B, Figure 83) with special wax. (See Exhibit K for instructions on the application of the wax.)
3. Mount the fixture with the hemishell on the nose of the work spindle using eight Size 10-32 TPI socket-head cap screws. Tighten the screws lightly with equal torque. Using a 1/10,000 dial indicator, center the fixture on the spindle nose and tighten the cap screws evenly.
4. Mount the inside-diameter cutterhead interferometer (Figure 57), on the cutterhead spindle.
5. Using the 1/10,000 dial indicator, center the cutterhead spindle coincident with the outside of the hemishell.
6. Set the carriage-position interferometer to zero using the micrometer screw shown schematically in Figure 84.
7. Install the work coolant system and insert the 0.7-inch-radius diamond tool.
8. Using the coarse feed of the inside-diameter cutterhead, turn the inside radius to a depth of 0.005 inch at 0.002 inch/revolution. The last two cuts must have a maximum depth of 0.002 inch and a feed rate of 0.002 inch/revolution. Size to $3.99^{+0.000}_{-0.001}$ inch. All stock removal is accomplished with oil coolant supplied at a rate of 1/2 to 1 qt/min. The work spindle speed is 800 to 1,000 rpm. Measurements are made with conventional inside micrometers.

Figure 84. CARRIAGE POSITIONING.

9. Remove the holding fixture with the hemishell from the work spindle.
10. Partly immerse the holding fixture in water heated to about 200° F. When the wax has fully softened, remove the hemishell from the fixture.
11. Remount the hemishell on the holding fixture (1053-A, Figure 60), using the special wax. (See Exhibit K for instructions on the application of the wax.)
12. Remove the inside-diameter cutterhead from the cutterhead spindle.
13. Mount the holding fixture with the hemishell on the work spindle with eight Size 10-32 TPI socket-head cap screws evenly and slightly tightened.
14. Using the 1/10,000 dial indicator, center the hemishell coincident with the axis of rotation of the work spindle and evenly tighten the socket-head cap screws.
15. Using the 1/10,000 dial indicator, center the cutterhead spindle with its axis of rotation concentric with the center of the outside spherical surface. To do so, move the carriage until a constant reading is noted on the dial indicator when scanning the outside diameter of the hemishell.
16. Set the carriage position interferometer to zero.
17. Install the outside-diameter cutterhead on the cutterhead spindle (shown in Figure 56).

18. Install the coolant distribution system.
19. Insert the conventional tungsten carbide tool in the cutterhead.
20. Using the coarse feed on the cutterhead, turn the outside diameter of the hemishell to a depth 0.005 inch with a feed rate of 0.002 inch/revolution of the work spindle, leaving 0.005-inch of stock over the final size. Remove the tungsten carbide tool and replace it with a 0.7-inch-radius diamond tool. Turn to a semifinish outside diameter of $4.501^{+0.000}_{-0.001}$ inch. The last two cutting operations have a maximum depth of 0.002 inch and a feed rate of 0.002 inch/revolution of the work spindle. All machining processes include the use of cutting-oil coolant. Measurements are made with conventional micrometers.
21. Remove the hemishell with the holder from the hemishell turning machine.
22. Repeat Step 11.
23. Heat treat the hemishell in a controlled, nonoxidizing atmosphere to remove any residual stresses. Proceed as follows: Hold for three hours at 775° F, slow cool in a furnace at 50° F/hr to 500° F, then remove it from the furnace and air cool.
24. Mount the hemishell on the fixture (Item 1053-A, Figure 83, modified as in Figure 60). Use special wax in accordance with the instructions in Exhibit K.
25. Mount the hemishell and holder on the work spindle. Use Size 10-32 TPI cap screws. Tighten the screws evenly and lightly. With the 1/10,000 dial indicator, center the hemishell concentric with the axis of the work spindle. Use centering screws to position the hemishell (Figure 85). Firmly and evenly finish tightening the screws.
26. Center the carriage by scanning the outside diameter of the hemishell with the 1/10,000 electronic-type dial indicator mounted on the cutterhead.
27. Zero the carriage position interferometer.
28. Install the straight-edge diamond knife in the cutterhead and adjust the coolant system for a flow of from 1/2 to 1 qt/min. Check the temperature of the coolant thermocouple that is inserted in the coolant nozzle. The optimum temperature is 67.8° F.
29. Make a trial cut that is 50 to 100 microinches deep, starting at the edge of the spherical surface near the equator. The feed rate should be approximately

Figure 85. CUTTERHEAD SPINDLE STOP.

0.001 inch/revolution of the work spindle. As the cut approaches the pole, both the work spindle speed and the cutterhead spindle speed are retarded—the work spindle to about 200 rpm and the cutterhead to a speed that is barely perceptible. Cutoff the coolant supply and adjust the cutterhead interferometer to produce fringes. When undistorted bull's-eye fringes appear, the cut has reached the pole. The final motion of the cutterhead spindle is controlled by a micrometer stop, shown schematically in Figure 85. The proper adjustment of the micrometer stop is at that position where the undistorted bull's-eye fringe system first appears.

30. Start the coolant supply and readjust the work spindle speed to 800 to 1,000 rpm and the cutterhead spindle feed speed to 0.001 inch/revolution of the work spindle. Return the tool to the cut "start" position and advance the cutting tool 100 microinches using the microfeed. Repeat this cutting operation until the size is $4.500200^{+0.000000}_{-0.000100}$ inches. (From this size to the final operation, all measurements are made with the outside-diameter interferometer. The reference dimension is taken from a gage block or blocks calibrated by the National Bureau of Standards.) Continuing the same machining sequence, advance the tool in increments of 20 microinches until a size of $4.500040^{+0.000000}_{-0.000020}$ inches is measured. The final cut is made by advancing the cutting tool one half the difference between the measured diameter and the final diameter. This final adjustment is made with reference to the white-light fringe system in the cutterhead interferometer. If red fringes are used, each fringe represents 12.3 microinches.

31. Remove the holding fixture with the hemishell from the work spindle. Remove the hemishell from the fixture as described in Step 10.
32. Remount the hemishell onto the holding fixture (1053-B, Figure 83) using the special wax in accordance with instructions in Exhibit K.
33. Remove the outside-diameter cutterhead interferometer from the cutterhead.
34. Mount the holding fixture with the hemishell onto the work spindle using Size 10-32 TPI socket-head cap screws. Tighten lightly and evenly.
35. Using one of the two outside-diameter interferometers, center the hemishell coincident with the axis of rotation of the work spindle within five microinches or less. Where imperfect shapes exist, an averaging process will be required. (Shifting the hemishell and fixture assembly is accomplished with centering blocks, Figure 86, attached to the spindle during this operation.) Make a final tightening of the socket-head cap screws. Preferential tightening may be necessary to maintain a coincidence between the hemishell center and axis of rotation.
36. Install the outside-diameter centering interferometer (Figure 58) onto the cutterhead spindle.
37. Adjust the centering interferometer to produce a fringe system when looking at the hemishell at the equator. Rotate the cutterhead spindle 90 degrees to a position where the centering interferometer is directed at the pole in the outside diameter. Move the carriage until the fringe system is again reproduced in the interferometer. Rotate the cutterhead spindle back to its original position and observe the fringes. Black zero-order fringes appear as a dot at both the equator and the pole when the operation is complete. The sequence of adjustment must be repeated until the zero-order fringe appears at all observable positions.
38. Zero the carriage-position interferometer.
39. Remove the outside-diameter centering interferometer.
40. Face the end of the hemishell using a curved-edge diamond tool.
41. Mount the inside-diameter cutterhead interferometer. Install the curved-edge diamond knife.
42. Remount the coolant distribution system and set the flow to 1/2 to 1 qt/min.
43. Test the cut by scanning the inside diameter with the curved-edge diamond knife advancing the diamond knife about 100 μ in/scan until contact is made. After a full cut has been made over the entire surface, set the curved-edge

diamond knife for height to eliminate any surface imperfections at the pole. Adjust the interferometer in the inside-diameter cutterhead to produce bull's-eye fringes. Next, set the cutterhead stop by following the same sequence of operations described in Step 29.

44. Start the coolant supply and readjust the work spindle speed to 800 to 1,000 rpm and cutterhead feed speed to 0.001 inch/revolution of the work spindle. Return the tool to the "start" position clear of the work, and advance the tool 100 microinches using the microfeed. Repeat this operation until a size of $3.999800^{+0.000100}_{-0.000000}$ inches is achieved. (All diameter measurements are made with the inside-diameter measuring interferometer systems referenced to a gage block or blocks calibrated by the National Bureau of Standards.)

Continue the same machining sequence except advance the diamond knife in increments of 20 microinches until a diameter of $3.999960^{+0.000020}_{-0.000000}$ inches is measured. The final cut is made by advancing the tool one half the difference between the measured diameter and the final diameter. The gage-block dimension is selected equal to the final size. Thus, the difference in work size with respect to final size is determined by reading fringes in the cutterhead interferometer.

The machining procedure described here is believed to be the most accurate and economical. Important considerations are: (1) preservation of the diamond knife edge, (2) dissipation of heat sources which affect the final size and shape, and (3) strains resulting from the thermal effects of the special holding wax. Experimental work has progressed through Step 31.

The following is an example of the procedural changes which can be made as experience is gained: Initially, Step 23 was performed as Step 2. However, subsequent work demonstrated that the change in shape from stress relieving was less than 50 microinches; therefore, the hemishell could be heat treated later in the finish machining operation. Step 23 appears to yield the maximum benefit from the stress-relieving operation without jeopardizing the geometry of the work.