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Engineering and Equipment

MACHINE TOOL EVALUATION STUDIES

J. S. Oakwood

HASTER

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
CARBIDE**

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J. S. Oakwood

Oak Ridge, Tennessee

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ABSTRACT

A series of tests has been performed to evaluate specific machine-tool characteristics. Empirical data pertaining to horizontal turning machine spindles were collected under normal shop conditions. Some conclusions have been inferred from the data presented. It is the primary purpose of this report, however, to focus attention upon the present "state of the art" with respect to machine-tool capability.

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SUMMARY

Experiments were designed to evaluate such specific machine-tool characteristics as: parallelism of spindle axis to carriage travel, spindle axial and radial stiffness, and spindle axial growth and radial runout. Accumulated data from twelve machines were analyzed. Test data indicate that horizontal misalignment of the spindle and machine axes produces a taper in a part. There is also an indication that spindle growth, attributable to temperature variation, is a very serious problem.

INTRODUCTION

In any program to improve machining capabilities, the need for precise information about specific machine-tool characteristics is basic. A knowledge of the variability of machine-tool performance during the machining process is of the utmost importance. A thorough understanding of what happens and why it happens when a part is being machined must be obtained.

To satisfy this need, the Y-12 Plant initiated a program in May of 1965 to evaluate machine-tool performance. Specific characteristics were to be studied. Since spindles are a predominant problem, the initial efforts in the program were concentrated in that direction. Emphasis was placed on horizontal turning machines due to the fact that considerable work is performed on that type of equipment.

These data were to be used as a basis for upgrading existing equipment and improving operating and maintenance methods and procedures. Additionally, the data obtained will be used to improve the design of present and future equipment.

EVALUATION OF THE CHARACTERISTICS

INTRODUCTION

Twelve machines were used throughout the series of tests. Three types of machines were selected in the major overall category of horizontal turning machines, namely: engine lathes, duplicators, and numerically controlled machines. These three sub-groups were further divided into two machines each of two brands. Therefore, four machines for each of the three types comprised the overall total of twelve machines for the entire series of tests. The machines varied in age from one to fifteen years.

Tests were designed and test models established with the aid of the Y-12 Plant's Statistical Services Group. In order to obtain statistically significant data, the statisticians were consulted periodically while the tests were in progress. Raw data from each series of tests were statistically analyzed and significant results reported with each test.

PARALLELISM OF THE SPINDLE AXIS TO THE CARRIAGE TRAVEL

Experimental Outline

This experiment was designed to investigate the out-of-parallel conditions that exist between the spindle axis and machine axis on the twelve machines to be tested. Horizontal and vertical misalignment data were obtained statically, and the effects of these conditions were obtained dynamically from a machined test piece. Replicate static readings from an independent setup were obtained on six of the twelve machines tested for the purpose of estimating the measurement error.

Discussion

Fixturing for checking the misalignment statically is shown in Figure 1. The "parallel" fixture was fabricated by the Y-12 Maintenance Division and is periodically used by them for machine checkout. The fixture is pinned at the right end; has a straight, flat face in excess of 12 inches (denoted by X-Y); a cam for adjustment, and a spring tension at the left end to maintain position. It bolts directly to a face plate, or may be chucked. Figure 1 also illustrates the vertical position. To measure the misalignment between the spindle axis and the machine bed, the fixture is placed in position and zeroed at X and Y. The spindle is then rotated 180 degrees and zeroed at X and read at Y. The misalignment is $Y/2$. This procedure is then repeated for the perpendicular plane. The measurements were taken with a Cleveland amplifier and gage head moving with the carriage travel. The amplifier was capable of being read to ten microinches per division on the fine scale. The data obtained are reported in Table 1.

Steps in Test:

1. Zero the gage jet at "X" and "Y"
2. Rotate the spindle 180 degrees
3. Zero the jet at "X" and read "Y"
4. Repeat for vertical and horizontal misalignment (misalignment = $Y/2$)

Figure 1. PARALLELISM TESTS. (Static Test)

Figure 2 shows the setup for checking the misalignment dynamically. An aluminum test cylinder, approximately five inches in diameter, was machined over a distance in excess of twelve inches. The difference between diameters D_1 and D_2 , twelve inches apart, was measured by the Dimensional Inspection Department with a Moore measuring machine using a dual-head Cleveland amplifier. The difference in diameters D_1 and D_2 divided by two gives the taper per foot. The roundness at diameters D_1 and D_2 was also measured by the Dimensional Inspection Department on an Indi-Ron roundness measuring machine. Results of these tests are also reported in Table 1.

Figure 2. PARALLELISM TESTS. (Dynamic Test)

Table 1
PARALLELISM OF SPINDLE AXIS TO CARRIAGE TRAVEL
(All Data in Microinches)

Machine Number	Type	"Parallel" Fixture(1)				Machined Test Cylinder		
		First Run		Second Run		Taper Per Foot	Out of Roundness	
		Vertical	Horizontal	Vertical	Horizontal		D ₁	D ₂
144136	Engine Lathe - A	600 D	750 F	600 D	800 F	1,110	50	75
144137	Engine Lathe - B	800 D	200 B	850 D	150 B	175	25	50
131997	Engine Lathe - C	350 U	1,250 F	350 U 375(2) U	1,300 F 1,325(2) F	1,100	50	50
131999	Engine Lathe - D	700 D	550 F	750 D 750(2) D	550 F 600(2) F	200	60	125
135022	Duplicator - E	200 D	1,450 B	175 D	1,450 B	1,330 WT(3) 1,400 WOT(3)	50 25	25 75
135025	Duplicator - F	200 D	700 B	240 D	725 B	625 WT	50	50
129993	Duplicator - G	300 D	700 B			2,285 WT 2,200 WOT	60	50
124537	Duplicator - H	700 D	350 F			300 WOT	50	75
139423	Numerical Control - K	160 D	500 B			600	50	30
139427	Numerical Control - L	800 D	350 B			330	75	25
144079	Numerical Control - M	600 D	425 F			425	20	50
144080	Numerical Control - N	200 U	150 F			88	30	40

(1) D - Spindle Points Down; U - Up; F - Front; B - Back.

(2) A third run was made on these two machines, using the same setup as for the second run, but with a short time lapse between.

(3) WT - With Tracer; WOT - Without Tracer.

Summary of Results

On the twelve machines tested, the misalignment varied from 160 to 850 microinches in the vertical plane and 150 to 1,900 microinches in the horizontal plane, over the distance of twelve inches. A taper of 88 to 2,285 microinches per foot was obtained from a machined test cylinder that was approximately five inches in diameter.

Statistical Analysis

The results of the evaluation can be summarized statistically as follows:

1. A highly significant linear correlation exists between the horizontal misalignment of a machine and the taper cut on a cylindrical part (Figure 3) with this machine. This condition apparently exists on duplicators whether or not a tracer is used (Table 2).

Figure 3. PART TAPER AS A FUNCTION OF THE HORIZONTAL MISALIGNMENT.

Table 2
OUT OF PARALLELISM
(All Values in $\mu\text{in/ft}$)

Machine	Horizontal	Taper Per Foot of Machined Cylinder	
		With Tracer	Without Tracer
Duplicator E	1,450	1,330	1,400
Duplicator G	1,900	2,285	2,200

2. A highly significant difference exists between the misalignment conditions of machines within some brands. About 95 percent of the time it is estimated that a machine chosen at random from the types and brands observed in this experiment will exhibit a vertical misalignment condition between zero and 1,135 microinches/foot and a horizontal misalignment condition between zero and 2,100 microinches/foot.
3. No significant differences were noted in the misalignment conditions for the different machine types.
4. No significant differences were noted between brands for any machine type.
5. No significant correlation exists between the vertical misalignment of a machine and the taper of a part cut on this machine. (This statement may not hold true for parts of a different size and configuration other than the five-inch-diameter cylinder used in this experiment.)
6. No significant correlation exists between the vertical or horizontal misalignment of a machine and the out of roundness of a part cut on this machine.
7. The measurement error associated with an individual static misalignment reading is estimated to be ± 55 microinches/foot.

Theoretical Mathematical Evaluation

The effect on contoured parts caused by spindle misalignment in a horizontal plane has been explored mathematically. A spindle misalignment error of +4 to -4 mils in increments of 0.5 mil has been investigated for spherically contoured parts from one to twelve inches in radius. On a one-inch-radius part, cut on a machine with a 4-mil spindle misalignment, the maximum part radial error is 0.7 mil at 45 degrees. The radial error at the pole and equator approaches 0.5 mil. As the part radius increases, the radial error shifts toward the pole. For a twelve-inch-radius part cut on a machine with a four-mil misalignment, the radial error at the equator is 0.5 mil; at the pole it exceeds four mils. Similarly, a part cut on a machine with two-mil spindle misalignment has a two-mil radial error at the pole for a twelve-inch-radius part.

There appears to be a very significant correlation between horizontal spindle misalignment and the radial error introduced into a part with a fairly large radius. If the spindle misalignment is in the positive direction, toward the front of the machine, the part radial error is negative and vice versa.

Conclusions

It is general practice in some shops to offset the spindle axis from the machine axis. The theory, apparently, is that a vertical misalignment compensates for the part weight and a horizontal misalignment compensates for the cutting forces. However, this theory, or practice, seems to be in error since a horizontal misalignment is reproduced as: (1) a taper on a cylindrical part, and (2) a polar error on contoured parts of large radii. As for cutting forces, roughing cuts do not require accuracy and finishing cuts cause negligible deflection. The data in this test indicate that the alignment of the spindle axis to the machine axis should be maintained as accurately as possible.

SPINDLE AXIAL AND RADIAL STIFFNESS

Experimental Outline

Experiments were performed to test the axial and radial stiffness of the spindles on the twelve machines selected for the performance evaluation. These experiments were designed to test the stiffness with a known force. Duplicate readings were obtained on a number of machines for the purpose of estimating the measurement error. Checks were also made to ensure that there was no bias in the results due to the order in which the readings were taken.

The setup for testing axial deflection is shown in Figure 4 and for radial deflection in Figure 5. It should be noted that all tests were static tests. In each case a mechanical force was applied with the tool holder. The amount of applied force was measured with a Dillon force gage. Spindle deflection was measured with an LVDT and a microinch amplifier. The amplifier was capable of readings to ten microinches; smaller readings were estimated.

Discussion

The magnitude of the radial deflection on some machines was somewhat greater than might have been expected. Improperly adjusted bearings, or perhaps excessive bearing wear, is suspected. Parts machined on these units might be tapered, out of round, or have a poor finish. The duplicators had the highest readings in this category.

Figure 4. ARRANGEMENT FOR MEASURING AXIAL STIFFNESS.

Figure 5. ARRANGEMENT FOR MEASURING SPINDLE RADIAL STIFFNESS.

However, this situation is probably due to the fact that those particular duplicators were about ready for a maintenance repair and overhaul. It does not necessarily follow that duplicators exhibit more radial deflection than engine lathes. With all other conditions being equal, it would be expected that the two categories would be about equal with respect to spindle stiffness.

The numerically controlled machines exhibited a very small amount of spindle deflection under the applied force. This result was quite apparent on the machine with the air-bearing spindle. Practically no axial deflection was detected on this machine.

Summary of Results

Other investigators have established the fact that finishing cuts generate a force of about ten pounds. The maximum axial deflection obtained in this series of tests was near a value of one microinch per pound of applied force. Thus, under normal finishing conditions, errors due to axial deflection would be expected to be ten microinches or less. Radial deflection on engine lathes and duplicators varied from 250 to 1,750 microinches with a maximum force of 300 pounds. The same force on the numerically controlled machines produced a radial deflection that ranged from 150 to 225 microinches. Under normal finishing conditions, errors due to radial deflection can, therefore, be expected to be less than 60 microinches on duplicators and engine lathes and less than ten microinches on numerically controlled machines.

Statistical Analysis

Axial Deflection - An evaluation of the amount of axial deflection can be summarized as follows:

1. No statistically significant differences exist between the average spindle deflections observed on the different machine types (engine lathe, duplicator, numerical control). Average deflections for each machine type for each level of applied force are summarized in Table 3 and plotted in Figure 6.
2. No statistically significant differences exist between brands for any machine type.
3. Highly statistically significant differences in spindle axial deflection exist between machines within brands. These differences tend to increase as the applied force increases.
4. The measurement error associated with an individual spindle axial deflection reading is ± 6 microinches. The data indicate that a high deflection reading is about as precise as a low deflection reading.
5. Highly significant linear correlations exist between the spindle axial deflections and the applied force. These relationships are indicated in Figures 7 through 9.

Table 3
AVERAGE SPINDLE AXIAL DEFLECTION
(All Values in Microinches)

Applied Force (lbs)	Engine Lathes(1)	Duplicators(1)	Numerically Controlled Machines(1)
25	13	17	11
50	29	35	24
75	44	54	35
100	58	70	48
150	91	104	72
200	128	139	95
250	158	169	116
300	192	202	135

(1) Measurement error is ± 3 microinches.

Figure 6. AVERAGE SPINDLE AXIAL DEFLECTION FOR THE THREE MACHINE TYPES.

Radial Deflection - An evaluation of the amount of radial deflection can be summarized as follows:

1. Highly statistically significant differences exist between the average spindle deflections observed on the different machine types. Average deflections for each machine type for each level of applied force are reported in Table 4 and plotted in Figure 10.

Figure 7. SPINDLE AXIAL DEFLECTION FOR FOUR ENGINE LATHES.

Figure 8. SPINDLE AXIAL DEFLECTION FOR FOUR DUPLICATORS.

Figure 9. SPINDLE AXIAL DEFLECTION FOR FOUR NUMERICALLY CONTROLLED MACHINES.

Table 4
AVERAGE SPINDLE RADIAL DEFLECTION
(All Values in Microinches)

Applied Force (lbs)	Engine Lathes ⁽¹⁾	Duplicators ⁽¹⁾	Numerically Controlled Machines ⁽¹⁾
25	55	93	14
50	105	183	29
75	154	301	43
100	221	432	59
150	336	689	87
200	500	976	111
250	669	1,245	140
300	876	1,511	166

(1) Measurement error is ± 15 microinches.

2. Statistically significant differences between brands exist for duplicators and engine lathes at the higher levels of applied force. Average deflections for each brand for each level of applied force are pointed out in Figure 11.

Figure 10. AVERAGE SPINDLE RADIAL DEFLECTION FOR THE THREE MACHINE TYPES.

Figure 11. AVERAGE SPINDLE RADIAL DEFLECTION FOR SEVERAL INDIVIDUAL MACHINES.

3. Highly statistically significant differences in spindle radial deflection exist between machines within brands. These differences tend to increase as the applied force increases.
4. The measurement error associated with an individual radial deflection reading is ± 30 microinches.
5. Highly significant linear correlations exist between the spindle radial deflections and the applied force. These relationships are indicated by the graphs of Figures 12 through 14.

Conclusions

Axial deflection apparently is not a serious problem since it is only about one micro-inch per pound of applied force. Thus, for finishing cuts, generating a force of about ten pounds would not be objectionable. Radial deflection on some machines,

Figure 12. SPINDLE RADIAL DEFLECTION FOR THE FOUR ENGINE LATHES.

Figure 13. SPINDLE RADIAL DEFLECTION FOR THE FOUR DUPLICATOR LATHES.

Figure 14. SPINDLE RADIAL DEFLECTION FOR THE FOUR NUMERICALLY CONTROLLED MACHINES.

however, might be of significance. High radial deflection may indicate a condition of maladjusted or excessively worn bearings, or a damaged shaft. The air-bearing spindle was designed to have reasonably good stiffness characteristics. Compared to the standard ball-bearing spindle machines, this unit showed a relatively small amount of spindle deflection under the applied load.

SPINDLE RADIAL RUNOUT AND AXIAL GROWTH

Experimental Outline

This series of experiments was designed to investigate spindle axial growth and spindle radial runout. Spindle axial growth and radial runout have been investigated previously on specific machines. However, prior to this experiment, no attempt has been made to compare the different types and sizes of machining equipment. It was the purpose of this test to demonstrate the magnitude and severity of spindle axial growth and radial runout in an extended series of tests utilizing various machine types. Twelve machines were tested that were comprised of engine lathes, duplicators, and numerically controlled horizontal turning machines. Six runs of eight hours each were made on each machine. One loaded and one unloaded run was made at each of three spindle speeds: 21, 257, and 667 rpm. For the loaded run, a light cut was taken on a test piece and the runs were all eight hours long. For the low speed, the machines were operated continuously for eight hours; for medium speed, the machines were operated for six hours, turned off one hour, and then on for one hour; for the high speed, the machines were run for four hours, turned off for one hour, run for one hour, off again for one hour, and run for the final hour.

Discussion

Figure 15 is a photograph showing the equipment for testing both spindle axial growth and radial runout. A diagram of the components for measuring axial growth is shown in Figure 16, and for radial runout in Figure 17. Figure 18 presents a cross-sectional view, showing the machined test piece, the sensing elements, and the temperature probe locations.

The spindle ball, Figure 18, was fabricated from Invar which has a coefficient of expansion of approximately one microinch per inch of length per one degree Fahrenheit change in temperature. The ball spindle, of the same Invar material, was flanged and bolted inside the aluminum test piece, adjacent to the flat plate, to prevent heat from being transferred from the test piece to the ball when the test piece was cut. It is felt, therefore, that any axial movement of the ball was truly due to spindle growth. The magnitude of the spindle axial growth reported herein is apparently not too unusual. Rector⁽¹⁾ and other investigators^(2, 3) have reported growths of 5 to 8 mils.

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Figure 15. TEST ARRANGEMENT FOR MEASURING SPINDLE RADIAL RUNOUT AND AXIAL GROWTH.

Figure 16. COMPONENTS FOR DETERMINING SPINDLE AXIAL GROWTH.

Figure 17. COMPONENTS FOR DETERMINING SPINDLE RADIAL RUNOUT.

The sensing elements, shown in a close-up view in Figure 19, are Photocan Model PT-5 capacitance transducers. The growth signal from the proximity transducer is fed into a Model DG-400 Dynagage and is recorded on a Model G-11A Varian recorder. Before each run, the transducer was calibrated to the Varian recorder, using a suitable magnification. At the end of each run, the calibration was checked to detect any possible changes. An air gap of 20 mils was set between the transducer and the spindle ball. A much larger gap was necessary for checking axial growth than for checking radial runout. This different arrangement was needed to maintain linearity of magnification in the growth-sensing element. Since the spindle might grow as much as five mils during a run, a narrow air gap would become even smaller and the magnification would not remain constant.

The signal from the two runout transducers, after going through the Model DG-400 Photocan Dynagages, was fed into Krohn-Hite Model 335 filters. Trial runs before starting the actual tests indicated that filters were necessary to remove the background vibration associated with the operating equipment. From the filters, the runout signals were fed into a double-channel storage oscilloscope, Type 564 Tektronix.

T - Temperature	P - Dynagage Probes
T ₁ - Spindle Collar (front)	P ₁ - Runout Probe (horizontal)
T ₂ - Spindle Housing (front)	P ₂ - Runout Probe (vertical)
T ₃ - Spindle Housing (rear)	P ₃ - Growth Probe
T ₄ - Motor or Switch Housing	
T ₅ - Room Temperature	

Figure 18. TEMPERATURE AND GAGE PROBE POSITIONS FOR SPINDLE RADIAL RUNOUT AND AXIAL GROWTH.

An air gap of five mils was maintained between the runout transducers and the spindle ball. The transducers were calibrated to the display screen of the oscilloscope, using a suitable magnification. The pattern could then be observed visually, or photographed for study. A Tektronix C-27 camera was used to photograph the runout pattern. The spindle ball was offset radially 0.5 to 1 mil, depending upon the machine being tested, to yield a circular pattern. If the spindle was perfectly centered, and all other conditions were optimum, the resulting runout pattern would simply be a point.

When tested in this manner, radial runout is displayed in a circular pattern, commonly known as the lissajous pattern.⁽⁴⁾ Figure 20 illustrates the manner in which two signals, or waves, are combined into the figure on the screen. The difference in the phase cycle, θ , between the two signals is utilized to produce the figure.

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Figure 19. PROXIMITY TRANSDUCERS.

The small numbers on the three diagrams in the figure represent corresponding time moments. The X axis is taken as the reference with the Y-axis signal leading by an angle, θ . At the moment of zero horizontal deflection, the vertical signal has progressed through θ and reached a height of $Y \sin \theta$ (Point 1). Thus, the intercept of the ellipse with the vertical center axis is $Y \sin \theta$, whereas the maximum height of the figure equals Y . A and B are the double intercepts. The phase angle used in this figure is 45 degrees. In the experiment, Angle $\theta = 90$ degrees. Figure 21 shows the various patterns obtained from a number of phase-angle shifts between zero and 180 degrees.

Typical radial runout patterns are shown in Figures 22 through 25. In each case the spindle was rotated for approximately 20 revolutions. The magnitude is the same, about 150 microinches for each.

Figure 20. GRAPHIC DEVELOPMENT OF A LISSAJOUS FIGURE SHOWING THE PHASE ANGLE BETWEEN TWO SIGNALS OF THE SAME FREQUENCY.

Figure 21. LISSAJOUS FIGURES OBTAINED FOR A NUMBER OF DIFFERENT PHASE ANGLES.

The proximity-transducer method of measuring spindle radial runout and axial growth has the following advantages over the contact-type gaging previously used: (1) there are no contact points to endure wear; (2) measurement at high rotational speeds is possible. This method was first used by Y-12 Development personnel in 1963. Runout was repeatedly measured to an accuracy of two microinches.

Summary of Results

Results of the experiments are summarized briefly in the sections that follow.

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Figure 22. STATIC RADIAL RUNOUT PATTERN FOR A MANUALLY ROTATED SPINDLE.

Spindle Axial Growth -

1. Spindle growth is dependent upon time, temperature, spindle speed, and load.
2. At low speeds, the spindle continues to grow for periods exceeding eight hours.
3. At high speeds, the spindle quickly reaches maximum growth, then cools back and levels off.
4. The magnitude of the spindle growth approaches five or six mils on some engine lathes and duplicators.

Radial Runout -

1. The magnitude of radial runout on the machines tested was about 150 microinches.

118340

Figure 23. DYNAMIC RADIAL RUNOUT PATTERN FOR A SPINDLE ROTATING AT 21 RPM.

Statistical Analysis

Analysis of the collected data is summarized in the sections that follow.

Axial Growth at Low Speed (21 rpm) -

1. Highly significant differences exist between machine types. Average spindle growth for each machine type is shown by the graph of Figure 26. Differences between machine types are not significant at the beginning of the run but become significant as the run progresses.
2. Highly significant differences exist between brands within machine types. The graphs of Figures 27 through 29 show the differences between brands for each machine.

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Figure 24. DYNAMIC RADIAL RUNOUT PATTERN FOR A SPINDLE ROTATING AT 255 RPM.

3. Highly significant differences exist between machines within some brands. The most notable of these differences occurs between the two numerically controlled machines, M and N, shown in Figure 30. Numerically Controlled Machine M, which has the air-bearing spindle, exhibits far less growth than the other machine.
4. For some machines, significantly more growth was noted when the machine was loaded than when it was unloaded. Average spindle growth for both loaded and unloaded conditions for each machine is given in Table 5.
5. The measurement repeatability of an individual reading is estimated to be ± 326 microinches. This number reflects measurement error plus changes in the machine from the first run to the second.

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Figure 25. DYNAMIC RADIAL RUNOUT PATTERN FOR A SPINDLE ROTATING AT 667 RPM.

Axial Growth at Medium Speed (257 rpm) -

1. The numerically controlled machines exhibit significantly less spindle growth than either the engine lathes or the duplicators. There is no significant difference between the growth observed on the engine lathes and that observed on the duplicators. Average spindle growth for each machine type is indicated in Figure 31.
2. No significant differences exist between brands within any machine type.
3. Highly significant differences exist between machines within some brands. Differences between Numerically Controlled Machines M and N are portrayed in Figure 32.
4. For most machines, significantly more growth was noted when the machine was loaded than when it was unloaded. Average spindle growth for both loaded and unloaded conditions for each machine is given in Table 6.

Figure 26. AVERAGE SPINDLE GROWTH AT LOW SPEED FOR THE THREE TYPES OF MACHINES TESTED.

Figure 27. AVERAGE SPINDLE GROWTH AT LOW SPEED FOR THE FOUR ENGINE LATHES.

Figure 28. AVERAGE SPINDLE GROWTH AT LOW SPEED FOR THE FOUR DUPLICATOR LATHES.

Figure 29. AVERAGE SPINDLE GROWTH AT LOW SPEED FOR THE FOUR NUMERICALLY CONTROLLED MACHINES.

Figure 30. AVERAGE SPINDLE GROWTH AT LOW SPEED FOR TWO NUMERICALLY CONTROLLED MACHINES WITH DIFFERENT SPINDLES.

Table 5
AVERAGE SPINDLE GROWTH AT LOW SPEED
(21 rpm).

Machine	Average Spindle Growth (microinches)	
	Loaded(1)	Unloaded(1)
Engine Lathe A	793	722
Engine Lathe B	1,025	970
Engine Lathe C	460	547
Engine Lathe D	793(2)	100(2)
Duplicator E	1,230	1,305
Duplicator F	1,118	914
Duplicator G	629	599
Duplicator H	890	648
Numerical Control K	560	695
Numerical Control L	602	592
Numerical Control M	53	73
Numerical Control N	541	119

(1) Measurement error is ± 199 microinches.

(2) Indicates that the difference between the loaded condition and the unloaded condition is significant.

Figure 31. AVERAGE SPINDLE GROWTH AT MEDIUM SPEED FOR THE THREE TYPES OF MACHINES TESTED.

Figure 32. AVERAGE SPINDLE GROWTH AT MEDIUM SPEED FOR TWO NUMERICALLY CONTROLLED MACHINES WITH DIFFERENT SPINDLES.

Table 6
AVERAGE SPINDLE GROWTH AT LOW SPEED
(257 rpm)

Machine	Average Spindle Growth (microinches)	
	Loaded(1)	Unloaded(1)
Engine Lathe A	2,111	1,840
Engine Lathe B	1,396(2)	901(2)
Engine Lathe C	960(2)	1,206(2)
Engine Lathe D	1,477(2)	930(2)
Duplicator E	1,708	1,662
Duplicator F	1,479(2)	968(2)
Duplicator G	1,512(2)	867(2)
Duplicator H	1,604(2)	1,251(2)
Numerical Control K	939(2)	434(2)
Numerical Control L	852(2)	656(2)
Numerical Control M	94	74
Numerical Control N	724(2)	342(2)

(1) Measurement error is ± 227 microinches.

(2) Indicates that the difference between the loaded condition and the unloaded condition is significant.

5. The measurement repeatability of an individual reading is estimated to be ± 466 microinches.

Axial Growth at High Speed (665 rpm) -

1. Highly significant differences exist between machine types. Average spindle growth for each type is indicated by the graph in Figure 33.
2. Significant differences exist between brands within machine types. Figure 34 shows the differences between the engine lathes.
3. Highly significant differences exist between machines within some brands.
4. For some machines, significantly more growth was noted when the machine was loaded than when it was unloaded. Average spindle growth for both loaded and unloaded conditions for each machine is reported in Table 7.
5. The measurement repeatability for an individual reading is estimated to be ± 747 microinches.

Radial Runout at All Speeds -

1. Runout does not change significantly as the run progresses for any speed.

Figure 33. AVERAGE SPINDLE GROWTH AT HIGH SPEED FOR THE THREE TYPES OF MACHINES TESTED.

Figure 34. AVERAGE SPINDLE GROWTH AT HIGH SPEED FOR THE FOUR ENGINE LATHES.

Table 7
AVERAGE SPINDLE GROWTH AT HIGH SPEED
(667 rpm)

Machine	Average Spindle Growth (microinches)	
	Loaded(1)	Unloaded(1)
Engine Lathe A	3,866(2)	3,229(2)
Engine Lathe B	4,375(2)	3,400(2)
Engine Lathe C	2,176	2,075
Engine Lathe D	2,153(2)	1,182(2)
Duplicator E	1,495	1,413
Duplicator F	1,798	1,415
Duplicator G	2,035	1,713
Duplicator H	2,230	1,920
Numerical Control K	1,009	792
Numerical Control L	1,036	761
Numerical Control M	146	143
Numerical Control N	982	573

(1) Measurement error is ± 308 microinches.

(2) Indicates that the difference between the loaded condition and the unloaded condition is significant.

2. Highly significant differences exist between machine types for each speed. Average spindle runout for each machine type at each speed is given in Table 8.

Table 8
AVERAGE SPINDLE RADIAL RUNOUT FOR MACHINE TYPES
(All Values in Microinches)

Speed (rpm)	Engine Lathes(1)	Duplicators(1)	Numerically Controlled Machines(1)
Low - 21	150	116	61
Medium - 257	151	119	63
High - 667	155	132	60

(1) Measurement error is ± 8 microinches.

3. No significant differences exist between brands within machine types for any speed.
4. Highly significant differences exist between machines within brands for each speed. Average runout for each machine at each speed is summarized in Tables 9 through 11.

Table 9
AVERAGE SPINDLE RUNOUT FOR ENGINE LATHES
(All Values in Microinches)

Speed (rpm)	Machine			
	A(1)	B(1)	C(1)	D(1)
Low - 21	130	141	158	171
Medium - 257	154	142	156	153
High - 667	143	145	163	170

(1) Measurement error is ± 20 microinches.

Table 10
AVERAGE SPINDLE RUNOUT FOR DUPLICATORS
(All Values in Microinches)

Speed (rpm)	Machine			
	E(1)	F(1)	G(1)	H(1)
Low - 21	103	96	149	128
Medium - 257	105	82	141	148
High - 667	120	97	154	157

(1) Measurement error is ± 20 microinches.

Table 11
AVERAGE SPINDLE RUNOUT FOR NUMERICALLY
CONTROLLED MACHINES
(All Values in Microinches)

Speed (rpm)	Machine			
	K(1)	L(1)	M(1)	N(1)
Low - 21	68	89	14	75
Medium - 257	67	85	17	84
High - 667	76	86	12	69

(1) Measurement error is ± 20 microinches.

5. No significant differences exist between the loaded and unloaded conditions for any speed.
6. The measurement repeatability associated with an individual runout reading is ± 54 microinches. This quantity is the same for all speeds.

The magnitude of the spindle growth for the three speeds varies from machine type to machine type. Very small differences exist between speeds for the numerically controlled machines. The rate of spindle growth increase is less for the slower speeds but the maximum average spindle growth attained differs little from speed to speed. Essentially the same holds true of the duplicators where the maximum average spindle growth attained increases slightly as the speed level increases. However, highly significant differences exist between speeds for the engine lathes where the maximum average spindle growth attained at the low speed is 1,259 microinches compared to 1,834 microinches for the medium speed and 3,570 microinches for the high speed.

The effect of cutting the machine off also varies from machine type to machine type. For the medium speed, the decrease in the average spindle growth was 127 microinches for the numerically controlled machines compared to 719 microinches for the duplicators and 846 microinches for the engine lathes. For the high speed, the decrease in the average spindle growth for the first hour the machine was off was 247 microinches for the numerically controlled machines compared to 926 microinches for the duplicators and 2,050 microinches for the engine lathes.

Spindle growth as a function of time for Engine Lathe A at the three different spindle speeds is shown by the graph of Figure 35. It is interesting to note that at the lower speeds the spindle never really reaches its maximum growth. At a higher speed, the spindle quickly warms up to its maximum growth, then cools back and levels off. This behavior seems to be typical of all machines. Figure 36 shows growth plotted against time for three machines at the higher speed.

The growth pattern is similar for all machines—quick maximum growth and then cooling back to the operating level. The difference in magnitude is also interesting, ranging from 1,100 microinches for Numerical Control Machine N, 2,000 microinches for Duplicator G, and 3,800 microinches for Engine Lathe A. Special long runs (12 hours) were made on two machines. These tests indicated that spindles continue to grow up to eight or ten hours, even when running at operating speeds of 255 rpm.

In most cases there is a significant linear correlation between the temperature taken at the various positions on the machine and the spindle growth. Outstanding examples are shown in Figures 37 through 39. Coefficients of determination, d , (given in %) that measure the proportion of variation in spindle growth attributable to variations in temperature are given for each situation. Relationships between room temperature and spindle growth are not shown because in most cases there is no significant correlation between them.

The coefficient of determination, d , mentioned earlier in this report is related to the coefficient of correlation, r , in that $d = r^2$. It is possible to interpret " d " as being that proportion of the variability in a dependent variable which is explained by its association with the independent variable. Referring to Figures 37 through 39,

Figure 35. AVERAGE SPINDLE GROWTH FOR ENGINE LATHE "A" AT THREE DIFFERENT SPEEDS.

Figure 36. AVERAGE SPINDLE GROWTH AT 665 RPM FOR THE THREE TYPES OF MACHINES TESTED.

where $d = 0.90$, it might be said that 90 percent of the variability of the spindle length is associated with, or attributable to, the variability in temperature.

Figure 37. SPINDLE GROWTH AS A FUNCTION OF TEMPERATURE FOR A LOADED ENGINE LATHE AT LOW SPEED. (Lathe D)

Figure 38. SPINDLE GROWTH AS A FUNCTION OF TEMPERATURE FOR AN UNLOADED DUPLICATOR LATHE AT LOW SPEED. (Lathe H)

Figure 39. SPINDLE GROWTH AS A FUNCTION OF TEMPERATURE FOR A LOADED NUMERICALLY CONTROLLED MACHINE AT MEDIUM SPEED. (Lathe L)

Conclusions

Spindle growth presents a fairly serious problem in machining quality product. (Growths of about 5 mils are not unusual.) However, there is a good correlation between the spindle operating temperature and spindle growth. Instrumentation to indicate the spindle position and/or temperature would appear to be a good approach to the problem.

The usual shop method of dealing with spindle growth involves two steps: (1) allow additional material for further machining, and (2) run the machine for a period of time to warm up the spindle before taking a cut. The first of these is not really a solution, as the problem must eventually be faced; the second is only a partial solution. Spindles expand unevenly, depending upon time, temperature, spindle speeds, and load. When the machine is stopped to change tools or parts, the spindle cools and the problem is accentuated. Spindle warmup is customarily accomplished at low speeds. The test data indicate that it is better to warm up at operating speeds, or higher, and then cool back. When operating at high speed (665 rpm), the growth quickly reaches a maximum, then cools back and levels off. The data suggest, then, that spindle warmup be accomplished at relatively high speeds and then cool the spindle back to the normal operating speed.

Growths of less than 100 microinches at operating speeds were recorded on the machine having the air-bearing spindle. This unit was still under development at the time these data were taken. The concept appears to be quite promising, and may solve the growth problem of the future.

GENERAL CONCLUSIONS

This series of experiments was concerned primarily with spindles. The alignment of the spindle axis to the carriage travel, axial and radial stiffness, radial runout, and axial growth were investigated. Analysis of the collected data indicates that there are some fairly serious drawbacks to the present-day equipment.

Horizontal misalignment of the spindle and machine axis is a predominant maladjustment. It is quite troublesome when machining parts of certain configurations. It is reproduced as a taper on a cylindrical part. The ratio of taper to horizontal misalignment is one to one. The same ratio prevails as a polar error on contoured parts of large radii. Since alignment errors of 1.9 mil were detected, this could be quite serious.

Spindle axial deflection apparently is not too serious, ranging upward to about 0.2 mil on engine lathes and duplicators. Radial deflection, however, was of much greater magnitude, being nearly 1.5 mils in one instance. This situation might affect the roundness, finish, or taper of a part.

Spindle radial runout was not a major problem on the machines tested.

Spindle elongation (axial growth) is much more serious. Growth in excess of five mils was recorded. Spindle growth is dependent upon time, temperature, spindle speed, and load. A very high correlation was found between temperature and growth. Better control of the operating temperatures in conventional equipment would materially reduce the growth. One machine tested was equipped with an air-bearing spindle. The growth on this machine, at the speeds tested, did not exceed 0.15 mil. Perhaps this indicates a solution to the problem.

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