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SKIVING

PDO 6989213, Final Report

L. K. Gillespie, Project Leader

Project Team:
R. K. Albright

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Project Leader:
L. K. Gillespie
Department 822

Project Team:
R. K. Albright

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SKIVING

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Prepared by L. K. Gillespie, D/822, under PDO 6989213

Skiving can be performed on conventional lathes to produce parts having high length-to-diameter ratios or complex shapes. Tolerances of ± 0.001 inch ($25.4 \mu\text{m}$) can be maintained on many parts, but tolerances of ± 0.002 inch ($50.8 \mu\text{m}$) are more realistic for job-shop applications. For 303Se stainless steel, surface finish can be held to 32 microinches rms ($0.81 \mu\text{m}$), or less.

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THE BENDIX CORPORATION
KANSAS CITY DIVISION
P.O. BOX 1159
KANSAS CITY, MISSOURI 64141

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CONTENTS

Section	Page
SUMMARY.	6
DISCUSSION	7
SCOPE AND PURPOSE.	7
PRIOR WORK	7
ACTIVITY	7
<u>Background</u>	7
<u>Multidiameter Parts</u>	8
<u>Two-Diameter Parts</u>	14
ACCOMPLISHMENTS.	17
REFERENCES	18
APPENDICES	
A. ANALYSIS OF CUTTING FORCES AND DEFLECTIONS	19
B. ECONOMICS OF SKIVING	28
DISTRIBUTION	33

ILLUSTRATIONS

Figure		Page
1	Comparison of Skiving-Tool and Form-Tool Geometry.	8
2	Various Tool Positions During the Skiving of a Part Having Only One Diameter.	9
3	Specimen Geometry Used for Machining Sequences 1 Through 3	10
4	Workpiece and Skiving Tool, as Viewed From Front of Tool (P-89647)	11
5	Illustration of Compound Approach Angles.	14
6	Front View of Skiving Tool and Part Produced in Machining Sequences 4 and 5.	15
A-1	Illustration of Geometry Variables.	20
A-2	Definition of Cutting Variables	21
A-3	Tooling Arrangement for Skiving on Two Lathes.	25
A-4	Calculated Variation in Cutting Force F_C as a Function of Tool Travel for Five-Diameter Part Shown in Figure 3.	26
A-5	Variation in Skiving Cutting Force F_C as a Function of Tool Travel for Two-Diameter Part Shown in Figure 6	26
A-6	Variation in Conventional Cutting Force as a Function of Tool Travel for Part Shown in Figure 6	27

TABLES

Number		Page
1	Tool Geometry Used for Study.	12
2	Skiving Repeatability for Five-Diameter 6061-T6 Aluminum Parts.	13
3	Skiving Repeatability for Two-Diameter 303Se Stainless-Steel Parts	16
A-1	Typical Values of Tan α	24
B-1	Time and Cost Comparison for Turning, Skiving, and Using a Screw Machine to Produce the Part Shown in Figure 3.	30

SUMMARY

The production of low-quantity, high-precision shafts and cylindrical components is a time-consuming and expensive operation. Skiving, which involves the use of a form tool, can be a considerably faster operation than the traditional single-point turning. However, little has been published on the process.

When this study was initiated, no data was available on the tolerance capabilities or economics of skiving as a method for producing precision components. The objective therefore was to determine the tolerance capabilities of the process and the economics involved in its use. This was accomplished through an evaluation of tool geometry, repeatability, and resulting surface finish. Although skiving has been used primarily with screw machines, its applicability to chucking lathes was investigated in this study. Two typical shaft shapes were evaluated through the use of 303Se stainless steel.

The investigation showed that skiving can maintain ± 0.001 -inch ($25.4 \mu\text{m}$) tolerances in 303Se stainless steel, although ± 0.002 inch ($50.8 \mu\text{m}$) is more realistic. The latter value represents less-than-optimum cutting conditions. When time is available to experiment with tool geometry, the smaller tolerance can be held; usually, however, time is at a premium.

Surface finishes of 32 microinches rms ($0.81 \mu\text{m}$), or less, were produced on 303Se stainless steel. In general, a 16-microinch rms ($0.41 \mu\text{m}$) finish on stainless steel represents a reasonable capability limit for the process. In some instances, better finishes can be produced.

An analysis of the costs involved indicates that skiving becomes economical at length-to-diameter ratios of approximately 10:1. It is also an economical method for producing irregular contours and such noncylindrical shapes as tapers and spheres. The economic evaluation, however, assumes that the previously defined tolerance capability is acceptable. Skiving is impractical for producing parts requiring ± 0.0002 -inch ($5.08 \mu\text{m}$) tolerances.

DISCUSSION

SCOPE AND PURPOSE

This study was initiated to determine the tolerance capabilities of the skiving process and the economics involved in its use. Although skiving has been used primarily with screw machines, its applicability to chucking lathes was investigated. Two 303Se stainless-steel shafts were evaluated as to tool geometry, repeatability, and resulting surface finish.

PRIOR WORK

While skiving had been used successfully at Bendix Kansas City to produce a few prototype parts, no attempt had been made to analyze or define the process capabilities.

ACTIVITY

Background

The production of short-run high-precision parts normally requires comparatively long setup and machining times. In production situations, cylindrical shapes such as shafts, collars, and other related items probably would be produced on fast, automatic screw-machine equipment. For quantities of 50 to 150 parts, however, the use of such equipment is not economical. Consequently, many of these parts are produced on manually operated chucker lathes--a process which requires the setup, adjustment, and feeding of many cutting tools.

Skiving provides the advantages of both short lathe-setup and short production-cycle times, since a single tool forms the entire part in one pass. It differs from conventional lathe-type form-tool methods in that the end of the part which is farther from the spindle is completed before the end nearer the spindle. This provides a more rigid workpiece during cutting than does the use of conventional form tools, since the spindle-end of the part is at its largest stock-size for most of the cut (Figure 1). In addition, the forces which act to bend the workpiece are often reduced since, for many parts, not all of the tool is cutting at any given time (Figure 2).

The diameters of the parts produced for this study ranged from 0.028 to 0.250 inch (0.711 to 6.35 mm). The part lengths varied from 2 to 10 times the part diameters.

Figure 1. Comparison of Skiving-Tool and Form-Tool Geometry

Multidiameter Parts

The original plan for the investigation was to produce an entire multidiameter part from 303Se stainless steel by the use of a single tool. In the first series of tests, parts having five diameters were attempted (Figures 3 and 4). In addition, the skiving tool was designed to cut off the part as well as form the diameters. For these tests, the smallest diameter was located at the cantilevered end of the bar stock.

Figure 2. Various Tool Positions During the Skiving of a Part Having Only One Diameter

D = DIAMETER
 ALL DIMENSIONS IN INCHES WITH
 MILLIMETER EQUIVALENTS IN PARENTHESES

Figure 3. Specimen Geometry Used for Machining Sequences 1 Through 3

The production of multidiameter, cut-off parts from 303Se stainless steel proved to be an impossibility. Not a single part was completed. The vibrating workpiece-end of the stock chipped the tool, and the forces involved broke the part from the stock long before the part was finished.

Parts were formed from 6061-T6 aluminum and cut off by the use of this technique, although the dimensional repeatability was poor. Sequences 1 and 2 in Table 1 indicate the tool geometries and machining conditions used. The dimensional characteristics of the aluminum parts are shown in Table 2. As indicated, the best standard deviation of the measurements was 0.00015 inch ($38.1 \mu\text{m}$) for Diameter B. Translated to piece-part drawing requirements, ± 0.0005 -inch ($12.7 \mu\text{m}$) tolerances obtained under the most favorable conditions and corresponding to $\pm 3 \sigma$ would be required in order for this process to be acceptable. As will be

Figure 4. Workpiece and Skiving Tool, as Viewed From Front of Tool

discussed later in this report, a more realistic production tolerance would be ± 0.002 inch ($50.8 \mu\text{m}$). Again, this is for an aluminum part, and not for a stainless-steel part.

Three factors which affected the results of the initial tests deserve additional comment. First, the smaller end of the workpiece should be located next to the headstock to obtain maximum stiffness for most of the cut. Although this seems contradictory to basic training, when the small diameter is at the cantilevered end, the tool is required to cut the small diameter while it is removing stock near the spindle for the

Table 1. Tool Geometry Used for Study

Sequence	Rake Angle (Deg)	Primary Approach Angle (Deg)	Machine Used*	Speed (RPM)	Feed Rate (IPM)**
1***	13	18	DVM		Hand
2***	30	18	HLV	1250	0.550
3***	30	18†	HLV	1250	0.550
4	30	34	HLV	900	1.000
5a	25	35	HLV	270 - 600††	0.25 - 0.5
5b	25	30	HLV	270 - 1250††	0.25 - 0.5
5c	35	35	HLV	350 - 600††	0.25 - 0.5
5d	35	30	HLV	270 - 600††	0.25 - 0.5

*Type of Hardinge lathe used to produce parts.

**1.0 ipm = 0.424 mm/s.

***Skiving tool also cut off part.

†A secondary approach angle of 28° was also used for this sequence.

††Operator changed spindle speeds and feed rates between parts.

larger diameters. This results in a large force at the free end of the workpiece, while the fixed end also is being turned. Measurable bending of the workpiece therefore occurs, and poor diameter repeatability is obtained.

The second factor is that skiving requires rigid equipment which operates smoothly with no vibration or slack in the ways. Small lathes, such as the Hardinge DVM which was used in the first test sequence, do not have sufficient rigidity for this type of operation. In addition, the lack of a power feed is a serious detriment when cutting a work-hardening material such as 303Se stainless steel. As shown in Table 2, the use of the small hand-fed lathe resulted in required tolerances up to ± 0.0023 inch (58.4 μm). The difference between Diameters A and B (Delta A-B), as indicated, was not as repeatable for Sequence 1 as was the size of a single diameter. Thus if two diameters must be held within a given tolerance, the minimum allowable tolerance would have to be that shown in the *Delta A-B* column of the $\pm 3\sigma$ Limits portion of the table.

Table 2. Skiving Repeatability for
Five-Diameter 6061-T6 Aluminum
Parts

Characteristic	Sequence*	
	1 (Inch)**	2 (Inch)
Small Diameter	0.200	0.048
Standard Deviation		
Diameter A***	0.00039	0.00024
Diameter B†	0.00057	0.00015
Delta A-B	0.00074	0.00013
±3σ†† Limits		
Diameter A	±0.0011	±0.0007
Diameter B	±0.0017	±0.0005
Delta A-B	±0.0023	±0.0004

*Cutting conditions for indicated
sequence are shown in Table 1.

**0.0001 inch = 2.54 μ m.

***Diameter A is the large diameter.

†Diameter B is the smallest
diameter other than that of the
retaining-ring groove.

††Sigma (σ) represents standard
deviation. If parts were pro-
duced under these conditions,
99.7 percent of all measurements
would fall within this range.

The third factor which influenced the results was the attempt to use the skiving tool to cut off the part. In a cut-off operation, the forces are high enough to bend the part. If a tool is near a workpiece which is being cut off, damage will occur to the tool, the part, or both.

During skiving, the complete diameters of the part ride over the top of the tool. If the cut-off tool is built into the skiving tool, the part will vibrate against the tool several hundred times before being cut off. This produces chamfered edges and broken ridges on the tool.

Even the use of a compound approach angle (Figures 4 and 5) failed to lower the forces enough to produce parts from 303Se stainless steel. Note that the tool shown in Figure 4 was designed to

Figure 5. Illustration of Compound Approach Angles

produce the smallest diameter at the spindle-end of the workpiece. (The part shown was produced by another tool, as indicated by the gap between the shoulder of the tool and the cut-off end of the part.)

Two-Diameter Parts

In the second series of tests (Sequence 4), two similar 303Se stainless-steel parts, each having only two diameters, were produced with the small diameter located near the headstock, as shown in Figure 1. The basic configuration of the parts is shown in Figure 6.

The first part had a small diameter of 0.070 inch (1.778 mm); by shimming the tool, the second part, having a small diameter of 0.056 inch (1.422 mm), was produced. A feed rate of 1.0 ipm (0.424 mm/s) was used to make these parts. A separate cut-off tool was used to sever the workpieces from the bar stock.

The results of the tests are shown in Table 3. As indicated, piece-part prints would have to allow tolerances in the order of ± 0.0033 inch (83.8 μm) to accommodate 99.7 percent of the parts produced by the tools used. To complete such a part, a second operation for facing the cut-off end would be required. (This also would be required in a conventional single-point turning operation.)

In the final tests (Sequence 5), four tool geometries were evaluated to determine which one would produce the most consistent results. To produce these parts, the bar stock was faced and then advanced to the shoulder of the skiving tool. After the part was skived, it was cut off.

In the sequence described, the skiving tool did not produce any part lengths; the length of the large diameter was controlled by the repeatability of the collet, and the length of the small diameter would have been controlled by a second facing operation. While this approach provided much better diameter repeatability, it necessitated an additional facing operation.

Figure 6. Front View of Skiving Tool and Part Produced in Machining Sequences 4 and 5

Feed rates from 0.25 to 0.50 ipm (0.1 to 0.2 mm/s) were used in the test. The time required to skive and cut off a part was 3.5 minutes, not including the time required for facing the cut-off end.

This last technique (Sequence 5) produced parts having surface finishes from 4 to 30 microinches (0.1 to 0.76 μm) with 16 microinches (0.41 μm) being typical.

As shown in Table 3, parts having tolerances of ± 0.0005 inch (12.7 μm) could be produced by using Tool 5a. However, for the production of a variety of short-run parts from different materials, tolerances of at least ± 0.001 inch (25.4 μm) seem more realistic.

In production situations, the time required to build several tools in order to determine the best tool geometry for a given configuration usually is not available. As a result, optimum tool geometries are not used, and the repeatability of the process consequently suffers. As shown by the results of the

Table 3. Skiving Repeatability for Two-Diameter 303Se Stainless Steel Parts

Characteristic	Sequence*					
	4** (Inch)†	4** (Inch)	5a*** (Inch)	5b*** (Inch)	5c*** (Inch)	5d*** (Inch)
Small Diameter	0.070	0.056	0.070	0.070	0.070	0.070
Standard Deviation						
Diameter A	0.0018	0.0013	0.00007	0.0007	0.0006	0.00009
Diameter B	0.0017††	0.0011†††	0.0002	0.0003	0.0066	0.0004
Delta A-B	0.0010	0.0011	0.0002	0.0003	0.0006	0.0004
±3σ Limits						
Diameter A	±0.0054	±0.0039	±0.0002	±0.0002	±0.0002	±0.0003
Diameter B	±0.0051	±0.0033	±0.0005	±0.0008	±0.0018	±0.0012
Delta A-B	±0.0030	±0.0033	±0.0005	±0.0008	±0.0018	±0.0012

*Cutting conditions for indicated sequence are shown in Table 1.

**The standard deviation of length measurements was 0.0011 inch (28.0 μm). Thus 99.74 percent of the parts would fall within ±0.0033 inch (83.3 μm) of the nominal length dimension.

***Parts produced in Sequence 5 had no measurable taper and were round within 0.0002 inch (5.08 μm).

†0.001 inch = 25.4 μm.

††These specimens typically had 0.0008-inch (20.3 μm) taper in the large diameter and were 0.0008 inch out-of-round. Measurement standard deviations were 0.0004 inch (10.2 μm) and 0.0005 inch (12.7 μm), respectively.

†††These specimens typically had 0.0008-inch (20.3 μm) taper in the large diameter and were 0.0010 inch (25.4 μm) out-of-round. Measurement standard deviations were 0.0004 inch (10.2 μm) and 0.0007 inch (17.8 μm), respectively.

Sequence-5 tests in Table 3, a tool which is close but not optimum can produce parts requiring tolerances as much as ± 0.0018 inch ($45.7 \mu\text{m}$).

As a general observation, the angles and techniques described in References 1 through 6 appear to be valid recommendations. While no firm recommendations can be made concerning functional length-to-diameter ratios, it is apparent that ratios of 10:1 can be produced by this process. Although tolerances of ± 0.0005 inch ($12.7 \mu\text{m}$) can be maintained under some conditions, tolerances of ± 0.001 inch ($25.4 \mu\text{m}$) are more realistic. To cover a wide variety of shapes and materials, tolerances of ± 0.002 inch ($50.8 \mu\text{m}$) should be allowed. Each of these observations agrees with the comments made in References 1 through 6.

Additional considerations concerning cutting forces, deflections, approach angle, and tool travel are presented in Appendix A of this report. Economic considerations are discussed in Appendix B. As shown by the material presented, skiving forces are considerably higher than forces involved in longitudinal turning, but lower than those encountered with conventional form tools. There is little economic advantage in using skiving for producing most turned parts. Skiving is advantageous for the production of long, narrow workpieces (having an L-to-D ratio of approximately 10:1) and for shapes which cannot be readily turned.

The availability of Swiss Automatic Screw machines (in which the stock is advanced past the cutting tools) eliminates much of the need to use form or skiving tools for the production of long, narrow parts. The inability of skiving to maintain close tolerances is the primary limitation.

ACCOMPLISHMENTS

Skiving has been shown to be a practical machining process for some limited-production parts when tolerances permit its use. Tolerances of ± 0.002 inch ($50.8 \mu\text{m}$) can be readily maintained in cutting 303Se stainless steel provided that the skiving tool is not used to face-off the cantilevered end. Diameters as small as 0.050 inch (1.27 mm) and lengths of 0.500 inch (12.7 mm) can be produced.

REFERENCES

- ¹Herbert C. Linberg, "Skiving Calculations," *Screw Machine Engineering*, October, 1950.
- ²George T. Walsh, "Skive the Limit," *Automatic Machining*, December, 1956.
- ³"About Skiving--When to use It," *Automatic Machining*, June, 1959, pp 47-48.
- ⁴"Skiving Tools--Design and Application," *Automatic Machining*, April, 1960, pp 57-60.
- ⁵W. C. Lloyd, "Let's Try Skiving," *Tooling and Production*, September, 1964, pp 89-92.
- ⁶G. T. Walsh, "Skiving on Automatics," *American Machinist*, February 28, 1966.
- ⁷Frank W. Wilson, editor, *Tool Engineers Handbook*. New York: McGraw Hill, 1949, p 343.
- ⁸"Power and Force Requirements in Machining," in *Machining Data Handbook*, Machinability Data Center, Cincinnati, 1972, pp 869-882.
- ⁹H. K. Baumeister and R. A. Sebrosky, "Deflection and Stress in Tapered Beams," *Machine Design*, February 4, 1971, pp 82-83.

Appendix A

ANALYSIS OF CUTTING FORCES AND DEFLECTIONS

BASIC CONSIDERATIONS

The reason for the rather disappointing performance of skiving tools in cutting 303Se stainless steel can be understood through a review of the cutting forces involved. To simplify the analysis, consider the action of a flat-topped tool such as that shown in Figure 2. This tool, having a top surface that is $D_T/2$ below the center line of the spindle (Figure A-1) will obviously cut whenever a portion of the tool reaches diameter D_C . The width of the tool engaged in the cut increases from zero to L_C (Figure A-2). Once the leading portion of the tool reaches the center line, the length in the cut remains constant at L_C until Point C enters the cut. Tool forces then decrease gradually to zero.

The principal cutting force F_C in a turning operation (acting in the direction of tool travel) can be calculated from the following well-known equation.^{7,8}

$$F_C = 396,000 A_0 W_n, \quad (A-1)$$

where

A_0 = cross sectional area of chip = $L_{C_i} f$,

L_{C_i} = instantaneous length of tool in cut,

f = feed per revolution, and

W_n = unit power for workpiece material to be machined.

Therefore, once the cutter reaches its maximum width of cut L_C ,

where

$$L_C = \frac{D_C}{2 \tan \alpha} \quad (A-2)$$

Figure A-1. Illustration of Geometry Variables

from geometrical considerations, the cutting force is

$$F_C = \frac{396,000 D_C f W_n}{2 \tan \alpha} = \frac{396,000 D_T f W_n}{2 \tan \alpha \tan(\sin^{-1} D_T/D)}, \quad (\text{A-3})$$

where

α = approach angle,

D_T = diameter of workpiece after skiving,

D = diameter of workpiece stock, and

D_C = diameter at which tool begins to cut.

For this study, D_T was nominally 0.070 inch (1.78 mm), D was 0.250 inch (6.35 mm), α was 30° , and f was 0.001 ipr (25.4 $\mu\text{m}/\text{rev}$). For 303Se stainless steel, W_n is in the order of 1.7 hp/in.³/min, and for aluminum it is in the order of 0.3 hp/in.³/min.⁸

Figure A-2. Definition of Cutting Variables

For these conditions then, F_C for 303Se stainless steel would be 159 pounds (707 N); in aluminum, the force would be 28 pounds (124 N). This force causes both a bending and a torque on the workpiece. If the worst-case condition is considered, the force acts at a distance of $L - L_C/2$ from the spindle. The deflection at the center of the cut (i.e. at $L - L_C/2$) caused by this force is therefore

$$\delta = \frac{F_C (L - L_C/2)^3}{3 EI}, \quad (A-4)$$

where $L \gg L_C$.

When the effect of the taper is considered,

$$\delta = \frac{KF_C (L - L_C/2)^3}{3 EI}, \quad (A-5)$$

where

K = a correction factor for tapered beams ($K = 4.0$ for the geometry of this part)⁹,

δ = deflection,

E = modulus of elasticity, and

I = cross-sectional moment of inertia = $\frac{\pi D^4}{64}$.

For the part used in Sequence 5 of this study, L was 0.455 inch (11.56 mm) and L_C was 0.105 inch (2.67 mm). Thus the workpiece deflection $\delta = 0.0038$ inch (95.8 μ m) for 303Se stainless steel, under these conditions. The deflection of the aluminum part would be 0.002 inch (50.8 μ m).

These deflections result in tool chipping, chamfered edges, and taper on the workpiece. The vibrations associated with the deflections result in poor surface finish.

Although the calculated deflection for 303Se stainless steel is small, it is significant. First, the deflection is at the midpoint of the cut; i.e., the workpiece bends the indicated amount directly in front of the tool. The deflection is even greater at the cantilevered end of the cut. Second, any such measurable deflection during cutting will distort the shape of the workpiece.

These calculations assume normal cutting conditions; at low feed rates, work-hardening materials such as 303Se stainless steel may require from two to five times the normal cutting

force. This, in turn, increases the deflection by a similar amount. As a result, the majority of parts for which skiving is considered the most economical process would suffer greater deflection and much greater geometry distortion than that shown by these calculations.

POTENTIAL IMPROVEMENTS

Some approaches to minimizing workpiece deflection can be seen in Equation A-3. Increasing the approach angle α can significantly lower the cutting forces. A change from 18 to 45 degrees will reduce F_C by a factor of 3.0. Lowering the feed rate will help with most materials, but not with 303Se stainless steel. Because this material work-hardens at low feed rates, decreasing the feed rate would significantly worsen the capability. A lower feed-rate limit for this material appears to be 0.0005 ipr (12.7 $\mu\text{m}/\text{rev}$).

Theoretically, the approach angle could be increased to some value close to 90 degrees. In practice, this is not feasible because of the length of tool movement required to get all the tool to the center line of the part. To complete a part of length L_T , the tool must travel the distance T where

$$T = L_T \tan \alpha + \frac{D_T}{2 \tan(\sin^{-1} D_T/D)}. \quad (\text{A-6})$$

Table A-1 indicates the effect of angle α on this distance. The production of a 0.322-inch-long (8.18 mm) part with an approach angle of 80 degrees requires 1.922 inches (46.4 mm) of tool travel. A standard Hardinge HLV chucker lathe, however, can only feed up to 1.0 inch (25.4 mm) past the center line when using the setup shown in Figure A-3. The hand-fed Hardinge DVM lathes have an allowable cross-travel of 3.5 inches (88.9 mm).

The second major consideration is that the tool width T_W (Figure A-3) also must be greater as the approach angle increases, since

$$T_W = L_T \tan \alpha. \quad (\text{A-7})$$

For a width T_W of 1.0 inch (25.4 mm) and a part length of 0.322 inch (8.18 mm), the approach angle must not be greater than 72 degrees. A 1.0-inch-wide (25.4 mm) tool is the widest tool that can be used in the chucker setup shown in Figure A-3. Although longer tools can be used in the DVM lathe, the tools overhang the holder by a considerable amount. This condition also will produce undesirable deflections if T_W becomes too great.

For a given feed rate, increasing the approach angle will increase the time required to complete a part, since the total tool travel is increased.

Table A-1. Typical Values
of $\tan \alpha$

Angle α (Degrees)	$\tan \alpha$ Value
18	0.325
30	0.577
45	1.000
60	1.732
75	3.732
80	5.671
85	11.430
90	∞

The analysis presented thus far has assumed that the skiving tool was producing a single diameter. In practice, however, several diameters are usually produced by this type of tool. Because the skiving tool has several cutting-levels (Figure 3), the tool will contact the workpiece in an uneven line. Figures A-4 and A-5 illustrate how the cutting force F_C varies as the tool advances into the workpiece. These diagrams were prepared by calculating the length of the tool that was cutting at points along the cross-feed.

Figure A-6 illustrates the cutting force produced by conventional turning of the part shown in Figure 6. A comparison of Figures A-5 and A-6 shows that, in this case, skiving resulted in up to five times the cutting force required for conventional turning. A conventional form tool, however, would produce three times the force produced by the skiving tool.

An analysis of Equations A-3 and A-5 indicates that decreasing the stock diameter by a factor of 2.0 decreases the cutting force by a factor of 4.0, but it also increases the deflection by a factor of 4.0. Decreasing the stock diameter by a factor of 2.0 will similarly decrease the machining time by a factor of almost 2.0.

Figure A-3. Tooling Arrangement for Skiving on Two Lathes

Figure A-4. Calculated Variation in Cutting Force F_C as a Function of Tool Travel for Five-Diameter Part Shown in Figure 3

Figure A-5. Variation in Skiving Cutting Force F_C as a Function of Tool Travel for Two-Diameter Part Shown in Figure 6

Figure A-6. Variation in Conventional Cutting Force as a Function of Tool Travel for Part Shown in Figure 6

Appendix B

ECONOMICS OF SKIVING

The time required to skive a part can be calculated from the following equation.

$$t_{\text{skive}} = \frac{k}{fS}, \quad (\text{B-1})$$

where

$$k = L \tan \alpha + \frac{D_T}{2 \tan(\sin^{-1} D_T/D)}, \quad (\text{B-2})$$

t_{skive} = skiving time (minutes),

f = feed rate (ipr),

S = spindle speed (rpm),

D_T = diameter of finished part (inch),

D = bar-stock diameter (inch),

L = length of part (inch), and

α = tool approach angle.

For parts having more than one diameter, D_T should be the largest.

The time required to turn a part is expressed by Equation B-3.

$$t_{\text{turn}} = \frac{L}{fS}. \quad (\text{B-3})$$

Equation B-3 will predict something less than the full turning time if several different diameters are to be produced. If the difference between the diameters is small in comparison to the length of the part, the error will be extremely small. The equation assumes that plunge cuts are not required (i.e., the part can be completed by using only a facing-and-turning tool). The assumption is made that a separate cut-off operation would be required for both conventional turning and skiving.

When setup costs, tool costs, and facing and cut-off costs are included in the calculated cost of machining, Equations B-4 through B-6 will result.

$$C_{\text{skive}} = \frac{kNR_1}{60 fS} + t_1 R_1 + \frac{DNR_1}{60 fS} + C_{\text{tool}} N, \quad (\text{B-4})$$

where

C_{skive} = cost of skiving (dollars),

N = number of parts to make,

R_1 = hourly labor wage of lathe operator,

t = setup time for skiving, facing, and cut-off (hours), and

C_{tool} = cost of tool per part produced.

For operations involving only facing and turning,

$$C_{\text{turn}} = \frac{LNR_1}{60 fS} + t_2 R_1 + \frac{DNR_1}{60 fS} + C_{\text{tool}} N, \quad (\text{B-5})$$

and for operations involving plunge cuts of depths $d_1, d_2, \dots$,

$$C_{\text{turn}} = \frac{(L + d_1 + d_2 + \dots d_i)NR_1}{60 fS} + t_2 R_1 + \frac{DNR_1}{60 fS} + (C_{\text{tool}_1} + C_{\text{tool}_2} + \dots C_{\text{tool}_i})N, \quad (\text{B-6})$$

where

C_{turn} = cost of turning (dollars),

d_i = depth of plunge cut for i 'th diameter (For three plunge cuts, there will be three "d" terms.),

C_{tool_i} = cost of i 'th tool per part produced (For three plunge cuts and one turning cut, four " C_{tool} " terms will be required.), and

t_2 = setup time for turning.

The first term in Equations B-4, B-5, and B-6 represents the cost for time in the cut. The second term represents setup costs, the third term represents the cost of facing the bar stock and cutting off the part, and the fourth term represents tool costs. These equations assume that feed rates for facing, plunging, cutting-off, and turning are all the same. For long, slender parts, the error introduced by this assumption is minor.

The final column in Table B-1 presents cost-related data calculated by these last three formulas. The part shown in Figure 3 represents

Table B-1. Time and Cost Comparison for Turning, Skiving, and Using a Screw Machine to Produce the Part Shown in Figure 3

Method Used and Number of Parts	Cutting Time* (Hours)	Setup Time (Hours)	Facing and Cut- Off Time (Hours)	Tool Cost (\$)	Cam Cost (\$)	Total Cost (\$)
Conventional Turning						
100	0.2	3	0.17	24	0	24 + 3.37 R ₁ **
300	0.6	3	0.52	30	0	30 + 4.12 R ₁
500	1.0	3	0.87	34	0	34 + 4.87 R ₁
1000	2.0	3	1.74	45	0	45 + 6.74 R ₁
Skiving						
100	0.39	2	0.17	37	0	37 + 2.56 R ₁
300	1.17	2	0.52	43	0	43 + 3.69 R ₁
500	1.95	2	0.87	47	0	47 + 4.82 R ₁
1000	3.90	2	1.74	58	0	58 + 7.64 R ₁
Screw Machine						
100	0.07	4	0.06	42	400	442 + 4.13 R ₁
300	0.20	4	0.18	44	400	444 + 4.38 R ₁
500	0.34	4	0.29	47	400	447 + 4.63 R ₁
1000	0.67	4	0.58	55	400	455 + 5.25 R ₁

*Time in cut.

**R₁ = hourly labor rate.

the geometry for which the data are applicable. To produce the correct overall length, a subsequent facing operation would be required by each of the methods used to produce the parts. The amounts shown in the table represent the total cost to produce the indicated number of parts.

The use of high-speed-steel tools is assumed, in all cases. Turning tools were estimated to cost \$6 each, skiving tools \$25, and screw-machine tools, \$12. (For the lathe and screw machine, a front-turn tool, two plunge tools, and a cut-off tool are required.) Cut-off tools are estimated to cost \$6 each.

Feeds for turning 303Se stainless steel are 0.003 ipr (76.2 $\mu\text{m}/\text{rev}$), but skiving and plunge cuts are fed at 0.001 ipr (25.4 $\mu\text{m}/\text{rev}$). A spindle speed of 1200 rpm is used for all lathe turning and skiving operations, with a 3600-rpm speed assumed for the screw machine. Screw machine cams cost \$400 per set. Other values used in the calculations were as follows.

$D = 0.125$ inch (3.175 mm),

$D_T = 0.080$ inch (2.0 mm), and

$\alpha = 30$ degrees.

Setup times of 2, 3, and 4 hours were estimated for skiving, conventional turning, and screw-machine use, respectively. Tool-resharpening costs were estimated at \$1 per sharpening. Resharpening was estimated to average 1 screw-machine tool or 2 conventional tools for every 100 parts produced. Skiving was estimated to require the resharpening of 2 tools for every 100 parts produced.

As indicated in Table B-1, skiving the part shown in Figure 3 would *not* be the least expensive approach. For a part having a length-to-diameter ratio of 10:1, skiving would prove to be less expensive. It would also be less expensive if an additional "groove" tool or "back" turning tool were required. As shown in the table, the largest production cost factors are the setup and tool costs.

Skiving may be, in practice, the most economical process since a lathe operator would have to hand-feed, face, and turn tools to maintain the length requirements for each shoulder. As opposed to skiving, the cutting efficiency of conventional lathe tools is probably from 30 to 50 percent. Essentially, the more complex the shape or the higher the length-to-diameter ratio, the more likely that skiving is a suitable process. The relatively high cost of screw-machine cams rules out the screw-machine method when only the economics of cutting are involved.

In practice, tolerances and surface-finish requirements dictate the economics. For parts having tolerances of ± 0.0002 inch (5.08 μm), skiving is not a practical process.

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