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DRILLING MINIATURE HOLES, PART II

Topical Report

L. K. Gillespie, Project Leader

Project Team:
B. J. Neal
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C. P. Rome

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**Kansas City
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DRILLING MINIATURE HOLES, PART II

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July 1978

Prepared by L. K. Gillespie, D/822

Miniature components for precision electromechanical mechanisms such as switches, timers, and actuators typically require a number of small holes. Due to precision, materials, and part geometry, most holes are produced by conventional drilling techniques. Such techniques are tedious and often require trial and error to prevent drill breakage, and to minimize hole mislocation and hole diameter variations. An initial study of drill geometries and drilling techniques to produce 0.66-mm-diameter holes in stainless steel and brass indicates that positional tolerances of 50.8 μm can be maintained. With appropriate drills, a repeatability of $\pm 2.54 \mu\text{m}$ can be maintained. An analysis of the strengths and deflection characteristics of the eight drills utilized in this study indicated that the printed circuit board drills and the spiral-flute pivot drills had the most rigid features. This is consistent with the tests of locational and size accuracy. Drills of this size can be fed at feedrates of 25.4 $\mu\text{m}/\text{revolution}$ in brass and stainless steel without breaking. Once the drill point starts into the workpiece, the elastic stability of the drill is not a major factor in breakage.

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SUMMARY

Precision miniature electromechanical mechanisms typically require a number of precision miniature holes for rotating shafts and press fit pins. Because of the tolerances required, the hole depth, and the materials involved, conventional drilling approaches must be used. These approaches are tedious and require great care to prevent drill breakage and to assure high quality holes.

This study was initiated to determine which types of equipment commonly used to drill small holes minimized hole drilling problems and how drill geometry, feeds, and speeds affect the locational and size accuracy of these holes.

An analysis of drill breaking strengths indicates that most drills 0.66 mm in diameter will not break when fed at feedrates up to 25.4 μm per revolution. The printed circuit board drill and the spiral flute pivot drill were noticeably stronger than the other drill geometries tested. In addition, the printed circuit board drill typically experienced less thrust in drilling than other drills fed at the same rate. An analysis of elastic stability indicates that this mode of failure will not occur in existing drilling equipment unless the drill point fails to enter the workpiece.

DISCUSSION

SCOPE AND PURPOSE

The objective of this study was to determine which drilling variables and tool geometries result in minimum hole mislocation and maximum hole size consistency. The effects of three types of drilling machines and the effects of drill geometry, feeds, and speeds were evaluated.

PRIOR WORK

Small-hole drilling has been performed for several years at Bendix Kansas City, but no formal effort has been made to document speed, feed, geometry, material hardness, and sequence-of-cuts effects on size and location. More than 100 different pieceparts in production have required the use of drills 0.79 mm in diameter, or smaller. These pieceparts were produced on 13 different types of equipment, each of which has separate limitations.

ACTIVITY

Study Phases

This study was performed in three phases. The first phase¹ utilized a single machine to evaluate the effects of drill design, feedrate, spindle speed, and chip clearing on hole size and location. In this phase only a single hole was drilled in each specimen.

In the second phase, which is the subject of this report, analytical and empirical analyses were made of drill rigidity and its effect on hole location and size consistency. Typical breaking strengths were calculated as were torques and thrusts produced by drilling.

In the third phase,² patterns of holes were drilled with the most successful drills found in the first phase. These patterns were then evaluated by computer techniques to determine the optimum positional locations one could expect with the equipment used.

Because of the large number of observations made, this study is reported in three parts with each part corresponding to the phases just described. The third report includes the final conclusions of the study in addition to a discussion of the tests conducted during the third phase.

General Drill Characteristics

Strength and stability characteristics of twist drills have long defied analytical analysis. These innocuous appearing tools hide a variety of complex interactions between helix angle, flute length, web thickness, drill length, and clearances. To compound the problem, because drilling standards are very broad, drill manufacturers provide a wide variety of cross-sectional shapes when the *standard drill* is ordered from several different companies. The ability to select drills based on tool life and strength is becoming increasingly important in high volume situations and in low volume, high cost applications. In many situations it is essential because of short lead times to obtain the right tool the first time.

Because of the lack of analytical models, evaluating drill strengths has required experimental approaches such as described by National Twist Drill³. An alternative graphical method for estimating torsional rigidity is described by the same company⁴. This latter method requires a destructive sectioning of at least one drill of each geometry. These methods become time consuming if many geometries have to be evaluated and if calculations other than torsional rigidity are needed. In precision work, for example, it is important to know how much drill perpendicularity to the workpiece will affect hole locations. An analysis of side loads and resulting deflections will provide this information.

Drill Properties

Most twist drills have a cross-sectional configuration similar to that shown in Figure 1. As illustrated, the fluted area consists of a curved surface, the drill margin, and the clearance behind the margin. These latter two drill elements can be defined by two radii.

It is well known that any regular curved surface, such as the cross section of the flute, can be expressed by a second order polynomial of the form

$$C_1X^2 + C_2XY + C_3Y^2 + C_4X + C_5Y + 1 = 0. \quad (1)$$

This equation is easily obtained by determining five points at any cross section along the flute (Figure 1).

In practice, the points X_i , Y_i would be obtained by placing the drill in a V-block or collet, and then finding the axial centerline by rotating the drill. The easiest approach would be to place the V-block on a comparator and use a digital readout for the final determination of the centerline. After nulling the digital readout at the centerline dimensions, the flute would be

Figure 1. Cross Section of Drill

perpendicular to the axis. Having established the upper and lower bounds to the X, Y coordinates, the trace would be repeated, recording five X, Y locations. The five points should be taken as far apart as possible to improve accuracy. These five coordinates can then be reduced by means of a Gaussian elimination computer subroutine to produce the five C_i constants in Equation 1.

Once Equation 1 and the data shown in Figure 2 have been obtained, it is a straightforward but algebraically cumbersome problem to calculate a drill's cross-sectional area and moments of inertia. Unfortunately, most miniature twist drills used in production do not have a straight shank. As a result, the transition area (Figure 3) from flute to chucking diameter can significantly influence drill rigidity. In order to estimate this effect, the data in Figure 4 must also be obtained and used in inertia calculations.

If one makes a cross-sectional cut at more than one place along the flute length, the cross section will be rotated with respect to the first cut. This is the result of the drill helix (Figure 5). Because of this rotation, the twist drill is stiffer than a straight fluted drill with the same cross-sectional shape. For this reason, one has to calculate effective moments of inertia for the whole drill as opposed to actual moments of inertia for a specific section.

A computer program was developed to calculate the areas and moments of inertia of each drill used in this study. Table 1 provides some comparative measured and calculated results for the drills used in the first phase of this study.¹ The terms I_{max}

$$R_{\text{clear}} \cdot d\phi = d/2,$$

where $d\phi$ is given in radians.

$$\therefore d\phi = d/2R_{\text{clear}}.$$

$$\therefore \phi_R = \phi - d\phi = \phi - d/2R_{\text{clear}}.$$

Similarly,

$$\phi_T = \phi - (d - f/2)/R_{\text{clear}}.$$

Figure 2. Definition of Variables

and I_{min} are the maximum and minimum moments of inertia. The subscript $xeff$ indicates calculated effective drill properties. The modulus of elasticity E is given as is the density of the drill material. Further drill data are listed elsewhere.¹

As shown in Table 1, the master drill is the stiffest of all drills with the exception of the calculated value, I_{xeff} .

Drill Torques and Thrusts

As a prelude to evaluating drill strengths, it is necessary to consider the actual torques and thrusts encountered when drilling small holes. Figures 6 through 8 illustrate the measured thrust forces produced at feedrates up to 0.127 mm/sec in brass and aluminum. As illustrated, the thrust forces varied from 1.12 to 13.34 N. Table 2 shows that thrust in stainless steel was up to

RADIAL TRANSITION

STRAIGHT TAPER TRANSITION

STRAIGHT SHANK

Figure 3. Typical Shank-to-Flute Transitions

27 times larger than that in brass. The maximum thrust exhibited by any drill was 60.05 N.

The life of one printed circuit board drill was studied briefly. As illustrated in Figure 9, drill thrust rose to a maximum of 31.14 N after 50 holes had been drilled in 17-4 PH stainless steel. The hole diameter varied 7.62 μm in 94 holes. Life tests were discontinued after drilling 118 holes.

Previous work on drilling forces⁵ indicates that they follow the form of Equations 2 and 3.

$$P = S_1 f^a D^b \quad (2)$$

$$T = S_2 f^c D^d \quad (3)$$

Figure 4. Definition of Drill Geometry

where

P = thrust,

f = feedrate,

D = drill diameter,

T = torque, and

a , b , c , d , and the S_i terms are constants determined by regression analyses.

DRILL HAVING ZERO
DEGREE HELIX ANGLE

FLUTE CONTOUR
ROTATION

Figure 5. Helix Angle Effect of
Rotating a Section

Using these equations and Boston's constants (Table 3) for a 0.66-mm drill at a feedrate of 0.0003 inch per revolution (7.6 $\mu\text{m}/\text{rev}$) in an SAE 1020 steel would yield the following results.

$$P = 104,300 f^{0.87} d^{1.0} = 2.33 \text{ pounds (10.36 N), and}$$

$$T = 1740 f^{0.78} d^{1.8} = 0.0043 \text{ foot-pounds (0.00583 N}\cdot\text{m)}$$

$$= 0.051 \text{ inch-pounds.}$$

As shown in Table 2, this value of thrust is reasonably close to those measured in stainless steel. No empirical torque data are available with which to judge the accuracy of Equation 3 and Boston's torque constants.

Kumabe⁷ has published some similar equations, using drills approximately 0.75 mm in diameter. His equations are summarized in Table 4, and the constants he obtained are listed in Tables 5 and 6. Table 7 compares Boston and Kumabe's predicted results, which differ by a factor of two. Despite the discrepancy, the Equations 2 through 8 (Table 4) bracket drill forces reasonably.

None of these equations, however, include the effects of web thickness, helix angle, point geometry, and speed. Furthermore, Boston's values for S_1 and a_1 are based on results of drills 3.175 through 31.75 mm in diameter, with typical web thickness-to-diameter ratios of 0.185.

Table 1. Properties of Drills Used in First Phase of Study

Drill	Diameter (mm)	E (MPa)	A (mm ²)	I _{min} * (mm ⁴)	I _{max} * (mm ⁴)	I _{xeff} ** (mm ⁴)	ρ (kg/m ³)
Standard Twist	0.66	206820	0.1871	0.001582	0.007741	0.004661	8121.4
Printed Circuit Board	0.66	648036	0.1613	0.001207	0.005369	0.003205	15593.7
Spiral-Pivot	0.66	206820	0.1871	0.001748	0.008907	0.005452	8121.4
Bore-Size	0.66	648036	0.1548	0.000749	0.004661	0.003246	15593.7
Master	0.66	648036	0.2193	0.002664	0.008324	0.002664	15593.7
Flat-Pivot	0.66	206820	0.1871	0.001249	0.006285	0.001249	8121.4

*I_{min} and I_{max} are minimum and maximum moments of inertia, respectively.

**I_{xeff} represents the calculated effective drill properties.

Figure 6. Drilling Thrust in Brass

Figure 7. Drilling Thrust in Aluminum

Figure 8. Drilling Thrust in Brass for Printed Circuit Board Drill

Table 2. Drilling Thrust* for Brass, Aluminum, 303Se Stainless Steel, and 17-4 PH (H900 Condition) Stainless Steel Workpieces

Drill	Feedrate (mm/s)		
	0.212	0.600	1.060
	Drilling Thrust (N)		
Drill	Brass Workpiece**		
Printed Circuit Board	--	--	4.00
Chisel-Point	--	4.00	6.23
Bore-Size	1.38	2.40	4.58
Master (0.67 mm)	2.22	2.98	4.58
Master (0.55 mm)	2.00	2.89	4.18
Flat-Pivot	1.69	3.20	--
Countersink†	2.67	3.60	4.45
Gold-Head	2.80	6.01	8.23
Drill	Aluminum Workpiece		
Gold-Head	4.00	5.34	6.89
Countersink	1.29	2.00	3.20
Flat-Pivot	3.65	4.80	15.12
Chisel-Point	4.00	3.60	6.23
Master (0.67 mm)	1.78	4.89	7.56
Bore-Size	1.20	2.80	7.12
Master (0.55 mm)	1.60	2.80	6.01
Drill	303Se Stainless Steel Workpiece		
Master (0.55 mm)	7.65	9.07	--
Gold-Head	40.03††	--	--
Flat Pivot	26.24	34.25	--
Countersink	9.88	16.01	--

Table 2 Continued. Drilling Thrust* for Brass,
Aluminum, 303Se Stainless Steel,
and 17-4 PH (H900 Condition)
Stainless Steel Workpieces

Drill	Feedrate (mm/s)		
	0.212	0.600	1.060
	Drilling Thrust (N)		
	303Se Stainless Steel Workpiece (Continued)		
Master (0.67 mm)	8.01	10.01	--
Bore-Size	8.01	12.01	--
Chisel-Point	Drill bent, would not start hole.		
Drill	17-4 PH (H900 Condition) Stainless Steel Workpiece		
Bore-Size	13.88	20.02	--
Flat-Pivot	--	60.05	--
Master (0.55 mm)	9.79	17.79	--
Master (0.67 mm)	12.01	20.02	--
Countersink	24.02	24.02	--
Printed Circuit Board	12.01	22.24	--

*At 6000 RPM when drilling a 1-mm-deep blind hole.
Drills were 0.66 mm in diameter, except for one
master drill, which is 0.55 mm, and the combination
drill and countersink, which is 0.40 mm.

**In Brass workpieces, a peak force larger than shown
occurs at initial impact with chisel-point, gold-
head, and flat-pivot drills.

†Drill portion only.

††Thrust at which drill broke.

Figure 9. Performance of Printed Circuit Board Drill

Table 3. Constants Used With Equations 2 and 3*

Material	Material Hardness (R _B)	S ₁	S ₂	a	b	c	d
SAE 33 Aluminum	70	90,400	556	1.0	1.2	0.83	1.9
Leaded Brass	100	6,160	512	0.6	1.0	0.73	1.9
Cast Iron	179	25,800	347	0.73	1.0	0.69	1.7
Malleable Cast Iron	137	24,400	689	0.75	1.0	0.78	1.8
SAE 3150 Steel	196	108,500	1500	0.87	1.0	0.78	1.8
SAE 1020 Steel	131	104,300	1740	0.87	1.0	0.78	1.8
SAE 1035 Steel	156	96,000	1300	0.87	1.0	0.78	1.8
Carbon Tool Steel	152	133,100	1842	0.87	1.0	0.78	1.8
SAE 1112 Steel	217	74,100	1000	0.87	1.0	0.78	1.8

*Based on Boston's data for 3.175 to 12.700-mm-diameter drills⁵ with flood coolant, constants are only valid when thrust is given in pounds, feedrate in inches/revolution, drill diameter in inches, and torque in pound-feet.

Values for six types of aluminum alloys have also been published.⁶

Table 4. Kumabe's Formulas for Torque and Thrust

Workpiece Material	Hardness (R_B)	Formulas		Equation
		Torque	Thrust	
Brass	75	$T = S_2 f^c D^d$	$P = S_1 f^a D^b$	4
Mild Steel	80	$T = S_2 f^c D^d$	$P = S_1 f^a D^b$	5
Duralumin	45	$T = S_2 f^c D^d$	$P = S_1 f^a D^b$	6
Copper	45	$T = S_2 f^c (D/0.7)^d$	$P = S_1 f^a D^b$	7
Mild Steel With Coolant CCL4	80	$T = S_2 (f/10)^c (D/0.75)^d$	$P = S_1 (f/10)^a D^b$	8

Table 5. Constants for Kumabe's Torque and Thrust Equations (Values in Metric System)

Material	Material Hardness (R_B)	S_1	S_2	a	b	c	d
Brass	75	7.35	0.00137	0.46	1.08	0.65	1.3
Mild Steel	80	8.63	0.00167	0.57	1.14	0.8	2.3
Duralumin	45	1.37	0.00980	$0.96D-0.36$	2.0	$0.94D-0.3$	2.0
Copper	45						
($D \geq 0.7$ mm)		5.10	0.00108	$0.54D-0.87$	2.46	$0.68D-0.57$	2.14
($D < 0.7$ mm)		5.10	0.00108	$0.54D-0.87$	2.46	$0.68D-0.57$	4.8
Mild Steel	80						
With CCL4							
Coolant							
($D \geq 0.75$ mm)		23.54	0.00275	0.37	1.14	0.8	2.3
($D < 0.75$ mm)		23.54	0.00275	0.37	1.14	0.8	1.0

NOTE: With these constants, P will be in Newtons, D in mm, f in microns/revolution, and T in N·m. Data are based on small (≈ 0.75 -mm-diameter) drills, feeds of 1.2 to 10.8 microns/revolution, and a speed of 2020 rpm.

Table 6. English Conversion of Kumabe's Values

Material	Material Hardness (R_B)	S_1	S_2	a_1	a_2	a_3	a_4
Brass	75	5,780	595	0.46	1.08	0.65	1.3
Mild Steel	80	25,128	83,948	0.57	1.14	0.8	2.3
Duralumin	45	19.9	5.6	0.30D-0.36	2.0	0.356D-0.3	2.0
Copper	45						
($D > 0.028$ in.)		3,276	20.8	0.032D-0.87	2.46	0.108D-0.57	2.14
($D < 0.028$ in.)		3,276	292,890	0.032D-0.87	2.46	0.108D-0.57	4.8
Mild Steel	80						
With CCL ₄							
($D > 0.030$ in.)		3,845	42,469	0.37	1.14	0.8	2.3
($D < 0.030$ in.)		3,845	436	0.37	1.14	0.8	1.0

NOTE: With these constants, P will be in pounds, D in inches, f in inches/revolution, and T in inch-pounds.

Table 7. Torque and Thrust Predicted by Boston and Kumabe in Mild Steel Without Coolant

Diameter (mm)	Feedrate ($\mu\text{m}/\text{rev}$)	Boston: Twist Drills		Kumabe: Twist Drills	
		Torque (N·m)	Thrust (N)	Torque (N·m)	Thrust (N)
0.40	2.5	0.0010	2.460	0.0004	5.262
	7.6	0.0025	6.392	0.0011	9.839
	12.5	0.0037	9.968	0.0016	13.167
	25.4	0.0048	13.362	0.0028	19.483
0.66	2.5	0.0025	3.995	0.0014	9.150
	7.6	0.0059	10.476	0.0033	17.117
	12.5	0.0088	16.200	0.0049	22.899
	25.4	0.0115	21.712	0.0085	33.940
0.90	2.5	0.0045	5.529	0.0029	13.260
	7.6	0.0106	14.386	0.0069	24.803
	12.5	0.0158	22.432	0.0104	33.184
	25.4	0.0206	30.061	0.0180	49.153

Boston's data for 3.96-mm-diameter drills in SAE 1020 steel indicate that at low feed rates web thickness changes do not noticeably affect drilling torque. For larger drills, web thicknesses are significant.

Boston's data also indicate that at very slow speeds [below 70 SFPM (357 mm/s), 500 rpm] spindle speed does affect drill torque. The result is distinctly not linear, however. Since most small-hole drilling is performed at higher speeds, this should not cause major discrepancies; but it should be considered. Helix angles affect the results by the following ratios.

$$T = 0.02 (30 - \gamma_0) T, \text{ and} \quad (9)$$

$$P = 0.025 (30 - \gamma_0) P, \quad (10)$$

where γ_0 is the drill helix angle. Thus, a helix angle of zero degrees would increase torque by 60 percent and thrust by 75 percent. Boston's data also indicate that drill breaking strength is nearly independent of helix angle.

Drill Breaking Strengths

The torsional strength of drills is another facet which has received little attention in the literature. As will be shown

later, since drill thrust does not appear to be a significant cause of failure, torsional or bending strength must be. The analysis of torsional strength for each of these drills studied is given in Appendix A, and summarized in Table 8. Several factors make these calculations of strength subject to significant error. Most of the calculations require the use of an inscribed circle, such as that shown in Figure 10, to determine the maximum shear stress. More importantly, however, determining the shear stress at failure requires data not published by tool steel manufacturers. Tool steel failures are extremely sensitive to machining processes and type of loading. Consequently, values of torsional shear stress at failure are not published by steel manufacturers.

For this study, it is assumed that the yield strength is a representative value of the maximum shear stress. This assumption appears to be verified by Hamaker's work,⁸ which found tensile and yield strengths to be nearly the same value for tool steels, and Roark's observations⁹ that the torsional modulus of rupture for solid bars varies from 80 to slightly over 100 percent of the ultimate tensile strength.

By measuring the size of circle which could be inscribed within each drill studied, and inserting these values into Roark's equations (Appendix A), the torque values shown in Table 8 were obtained. The technique by Carter and Oliphint was used for the flat pivot drill.¹⁰ Hopkins' text¹¹ was also utilized in this analysis.

By comparing the torque values in Table 8 with the predicted torques shown in Table 7, one can see that even by drilling at a feedrate of 25.4 $\mu\text{m}/\text{rev}$, breakage by drill torque alone should not occur. As drills become dull, torque does increase, however, and would increase the probability of failure by this mechanism.

It is significant to note that based on the calculated maximum allowable torques, the printed circuit board drill and the spiral pivot drill are much stronger than the other drills. These two drills consistently also produced more accurate holes than did the other drills, as indicated in the first phase of this study.¹

For larger drills, estimate of drill breaking strength can be obtained from the following formula.¹²

$$T_{\text{break}} = 0.0075D^3, \quad (11)$$

where

T_{break} is the torque in N·m at which a standard cross-section, high-speed drill of diameter D (mm) will break.

Table 8. Drill Strength Data

Drill	Inscribed Diameter D_i (mm)	Drill Material	Assumed Drill Yield Strength (MPa)	Maximum Allowable Torque (N·m)
Printed Circuit Board	0.28	Carbide	1930	0.1955
Bore-Size	0.27	Carbide	1930	0.0193
Spiral-Pivot	0.30	HSS	2999	0.4530
Master	0.30	Carbide	1930	0.0330
Flat-Pivot	*	HSS	2999	0.0265
Standard Twist	0.30	HSS	2999	0.0300

*Not required for this drill.

For a 0.66-mm-diameter drill, this predicts a breaking torque of 0.00496 N·m. This is roughly one-fifth the torque predicted by a more thorough analysis of drill cross sections. The reason for the difference is that small drills tend to have stiffer cross sections than larger drills, and Equation 11 does not take this into account. If Equation 11 and Table 7 are valid for these small drills, it would be impossible to drill 76.2 $\mu\text{m}/\text{rev}$ without breaking the drill.

As reported elsewhere,¹³ 0.75-mm-diameter circuit board drills routinely drill at conditions producing 0.014 N·m and, at 42.5 mm/s in this material, withstand 17.8-N thrust forces. Equation 11 predicts breakage at 0.0075 N·m for a 0.75-mm drill.

Based on the critical loads, Tables 7 and 8 (torques and thrusts), Table B-1 (recommendations), and the experimental results previously reported,¹ it would appear that drilling feedrates could be increased to 25.4 $\mu\text{m}/\text{rev}$ without causing drill breakage. As will be shown in the next section, buckling should also not be a problem at this feedrate. The printed circuit board drills and the HSS spiral pivot drills appear to be capable of much greater feedrates.

Figure 10. Inscribed Diameter for Strength Calculations

The effects of faster feedrates on hole size and hole location are not known, but the previously reported experimental data¹ on these drills indicate that $12.7 \mu\text{m}/\text{rev}$ feedrate does not cause any significant difference over a $76.2 \mu\text{m}/\text{rev}$ rate. In all cases, precision ground cutting lips will minimize hole size and location variances.

Elastic Stability

A significant portion of this study was devoted to calculating moments of inertia of the six drills. Although Oxford,^{3,4,14} DeBeer,¹⁵ and others have presented experimental data on drill rigidity, only Kronenberg¹⁶ has attempted to analytically derive moments of inertia. Kronenberg's analysis failed to account for the effect of a product of inertia term and for the impact of the helix angle. Both of these effects have been accounted for in the inertia calculations used in this study. The effective moments of inertia shown in Table 1 are weighted averages, based on the helix angle's effect of rotating the coordinate axis (Figure 5). Figure 11 illustrates how the theoretical inertia of a section varies with axial location.

Listed below are the specific questions that this study sought to answer.

1. Which drill design is influenced least by torsion, axial loads, and off-center (eccentric) loading?

Figure 11. Moment of Inertia and Effective Moment of Inertia

2. How can the drilling process be made faster?
3. What feeds and speeds give optimum acceptable loading?
4. Should tungsten carbide or high-speed steel be used?
5. What drill designs produce equivalent results?
6. How much does drill eccentricity or off-center loading affect critical loads?
7. How much does the helix angle affect the results?
8. What effect do small variations in diameter and flute shape have on the results?

It should be emphasized here that this was a study of commercially available drills and that it was primarily concerned with the fluted sections. Drill point geometries were not considered in this study, although their impact can be just as great as flute shapes and lengths.

Figures 12 through 16 illustrate the end conditions which were analyzed in this study. The initial condition (Figure 12) occurs before the drill ever contacts the workpiece. At certain critical spindle speeds, this cantilevered drill begins whipping or describing a circular path around the centerline of the spindle. Figure 13 shows the drill at the time of initial contact with the workpiece. As illustrated, these drills have a small radius at the center of the web. This is particularly visible on standard chisel-point drills. Figure 14 shows the drill a few seconds after the initial contact, and Figure 15 shows the drill at full depth. This condition does not represent a stability problem, but it does cause drill breakage as a result of chip packing in the flutes. Figure 16 illustrates the boundary conditions when drill jigs are used to guide the drill.

The velocity at which drill whipping would occur for the condition shown in Figure 12 was well over 1 million rpm for all drills. Thus, this mode of drill breakage is not likely to occur on any metal drilling equipment. An analysis of torsional and axial load effects on critical velocities indicates that they have little effect on this velocity.

The axial force $P_{critical}$, which causes buckling for the case shown in Figure 13, is given in Table 9 for each drill. These data are based on the formula

$$P = \frac{EI\pi^2}{L^2} \quad (12)$$

Figure 12. Drill Whipping

Figure 13. Initial Contact of Drill

Figure 14. Full Diameter Contact of Drill

Figure 15. Maximum Depth of Drill

Figure 16. Bushed Hole

where

E is the modulus of elasticity,

I is the effective moment of inertia, and

L is the flute length of the drill.

Since the predicted thrust in drilling does not even approach half (Table 7) of the lowest value in Table 9, pure buckling is not a likely source of drill breakage on these drills. Analyzing the fixed end-pinned end case shown in Figure 14 results in critical buckling forces twice as high as those predicted by Equation 12. Results for the conditions shown in Figures 15 and 16 require much greater forces yet, to cause breakage by buckling.

Table 10 indicates the deflection one would expect if the drill were slightly deflected from the centerline of the spindle. If, for example, a standard twist drill were initially out of alignment by $12.7 \mu\text{m}$ in 9.88 mm of flute, then a 4.448-N thrust would result in a hole mislocated by $15.2 \mu\text{m}$ at the hole entrance. A 13.34-N load would cause a mislocation of $25.4 \mu\text{m}$. The equation for this condition is

Table 9. Critical First Mode Loads: Fixed End - Free End

Drill	Diameter (mm)	E (GPa)	I_{xeff} (mm ⁴)	L (mm)	$P_{critical}$ (N)
Standard Twist	0.66	207	0.00466	9.88	97.9
Printed Circuit Board	0.66	648	0.06320	4.47	1027.5
Spiral-Pivot	0.66	207	0.00545	3.94	720.6
Bore-Size	0.66	648	0.003246	3.94	306.9
Master	0.66	648	0.00266	4.72	769.5
Flat-Pivot	0.66	207	0.00125	4.72	111.2

$$Y_{start} = \frac{C_1}{\sqrt{P/EI}} \tan (\sqrt{P/EI} L), \quad (13)$$

where

C_1 = initial tool deflection divided by flute length, and

P = applied thrust load.

Tables 9 and 10 indicate that the printed circuit board drill and the spiral-flute pivot drill are the most rigid drills because of their flute length, cross section, and drill material. Figure 17 indicates the load deflection curves measured for three of the drills used in this study. A 4.448-N lateral load deflected the printed circuit board drill 0.19 mm, the spiral flute pivot drill 0.50 mm, and the standard chisel-point drill by 1.90 mm. The measured deflections correlate closely to the predicted deflection.

$$Y = \frac{PL^3}{3EI}, \quad (14)$$

when the minimum moment of inertia is used rather than the calculated effective moment of inertia.

It is not surprising that the repeatability of hole size and location can be directly tied to the drill rigidity (Table 11) via Equations 12, 13, or 14. Each of these equations involves the product EI divided by, or into, the flute length L .

If the drilled hole begins off center from the spindle it will be even further off location at the hole exit. Galloway¹⁷ has

Table 10. Maximum Deflection for Fixed End - Free End,
Free End Initially Deflected*

Drill	Diameter (mm)	E (GPa)	I_{xeff} (mm ⁴)	L (mm)	Y_{start} (μ m)	
					P = 4.448 N	P = 13.344 N
Standard Twist	0.66	207	0.00466	9.88	15.2	25.4
Printed Circuit Board	0.66	648	0.00320	4.47	5.1	5.1
Spiral- Pivot	0.66	207	0.00545	3.94	5.1	5.1
Bore- Size	0.66	648	0.00325	3.94	5.1	5.1
Master	0.66	648	0.00266	4.72	5.1	7.6
Flat- Pivot	0.66	207	0.00125	4.72	7.6	10.2

*Initial deflection = 0.001285 mm/mm of flute.

shown that if the thrust is less than one-fifth of the critical buckling load, then the hole location at any point along the axis of the hole can be approximated by

$$Y_{deflection} = Y_{start} \exp\left(\frac{3d}{2L}\right), \quad (15)$$

where

$Y_{deflection}$ is the deflection of the hole,

d = depth of the hole, and

L = flute length of the drill.

Galloway's analysis also indicates that when spindle-to-quill misalignment and quill slide clearance are present, their influence on hole location follows the equation

Figure 17. Drill Deflection Measurements (Lateral Load at Point)

Table 11. Drill Performance Compared to Predicted Buckling Force

Drill	Size* Repeatability (μm)	Location* Repeatability (μm)	P _{critical} (N)
Printed Circuit Board	0.556	11.176	1027.5
Bore-Size	0.737	10.160	306.9
Spiral-Pivot	0.864	11.684	720.6
Gold-Head	3.632	19.558	Not Studied
Master	3.912	19.050	769.5
Flat-Pivot	4.978	28.448	111.2
Standard Twist	**	**	97.9

*In 303Se SST

**Would not start hole at 12.7 $\mu\text{m}/\text{rev}$; drill bent instead of drilling.

$$Y_{\max} = Y_{\text{start}} (\exp [3d/2L]) \pm \left(w \left[\frac{2L}{3} (\exp [3d/2L] - 1) - d \right] + c(\exp [3d/2L] - 1) \right), \quad (16)$$

where

w is the amount of misalignment, and c is the drill clearance.

Table 12 gives the effects on a hole location from an initial hole mislocation of 0.001285 mm per mm of flute length, a misalignment of 2.54 μm , and a quill clearance of ± 0.0025 mm. As shown, a flute length of 5.1 mm, producing a hole of the same depth, would result in a hole mislocated by up to 48.1 μm at the bottom of the hole. Without any misalignment or quill clearance, the bottom of the hole would be mislocated by 30.5 μm (Table 13).

ACCOMPLISHMENTS

This phase of the development indicated that repeatability of drill location and size can be predicted to a reasonable extent by a knowledge of a drill's modulus of elasticity, minimum or effective moment of inertia, and drill flute length. Techniques were developed to obtain these data from simple measurements.

Table 12. Maximum Drill Point Deflection With Misalignment, Drill Point Deflection, and Spindle Clearance

Flute Length L (mm)	Mislocation of Drill Point (μm)				
	Hole Depth d (mm)				
	0.063	2.50	5.08	7.60	10.00
1.0	7.62	--	--	--	--
2.5	10.2	32.9	--	--	--
5.1	10.2	20.4	48.1	--	--
7.6	12.7	20.4	35.4	63.5	--
10.2	15.2	20.4	32.9	50.8	78.7

Analyses of drill strength indicate that feedrates of $25.4 \mu\text{m}/\text{rev}$ can be used without experiencing drill breakage if the proper drill is used. Under normal conditions, neither buckling nor critical rotational velocities will occur. The solid carbide printed circuit board drill and the high speed steel spiral-pivot drills had the best strength characteristics as well as the most repeatable performance.

FUTURE WORK

The effects of drilling equipment on the accuracy of patterns of holes will be reported for the third phase of this study.²

Table 13. Drill Point Deflection for Initially Deflected Drill

Flute Length L (mm)	Mislocation* of Drill Point (μm)				
	Hole Depth d (mm)				
	0.63	2.50	5.08	7.50	10.00
1.0	2.5	--	--	--	--
2.5	5.1	15.2	--	--	--
5.0	7.6	12.7	30.4	--	--
7.5	10.2	15.2	25.4	43.1	--
10.0	15.2	17.7	27.9	40.6	58.4

*Ignores machine runout. Initial hole mislocation = 12.7 μm per 9.88 mm of flute length.

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Appendix A

STRENGTH CALCULATIONS

Appendix A

STRENGTH CALCULATIONS

FLAT-PIVOT DRILL

Carter and Oliphint's analysis¹⁰ of the shape shown in Figure A-1 indicates that for $90-\alpha$ greater than 1.047 radians the maximum shear stress can be calculated with formulas applicable to rectangular sections. For the drills of this study, $90-\alpha = 1.12$ radians. From Roark,⁹

$$\tau_{s \max} = \frac{T (3r + 1.86t)}{8t^2 r^2} \quad (A-1)$$

For $r = 0.33$ mm, and $t = r/3$,

$$\tau_{s \max} = \frac{4.07T}{r^3} = \frac{32.56T}{D^3} \quad (A-2)$$

Assuming that the maximum allowable shear stress is equal to the yield strength of the drill material, the torque to cause failure can be calculated. It should be noted that for carbide, yield strength equals tensile strength; but this is not necessarily true for high-speed steels. Manufacturers do not publish and, in fact, do not appear to have data on the tensile strength. Tensile strength is generally used to calculate torsional strength.

$$T_{\max \text{ allowed}} = \sigma_{\text{yield}} \frac{D^3}{32.56} \quad (A-3)$$

For HSS $\sigma_{\text{yield}} = 2999$ MPa (Table 14 or Table A-2).

Thus, for $D = 0.66$ mm,

$$T_{\max \text{ allowed}} = 0.0265 \text{ N}\cdot\text{m}.$$

MASTER DRILL

By Roark's analysis,⁹ (p 197) and Hopkins,¹¹ the maximum shear stress should occur at point b' (Figure A-2).

$$\tau_{s \max} = \frac{Tcb'}{K} \quad (A-4)$$

Figure A-1. Cross-Sectional
Geometry of
Flat-Pivot Drill

Figure A-2. Cross-Sectional
Geometry of
Master Drill

where

$$K = \frac{A^4}{40J}, \text{ and} \quad (A-5)$$

$$cb' = \frac{Di}{\left(\frac{1 + \pi^2 Di^4}{16A^2}\right)} \left[1 + \left(0.118 \ln \left[\frac{(1-Di)}{2R} \right] - \frac{0.238 Di}{2R} \right) \tan h \frac{2\phi}{\pi} \right]. \quad (A-6)$$

For $t = 0.2R$,

$Di = 0.30 \text{ mm}$,

$A = 0.2193 \text{ mm}^2$,

$D = 0.66 \text{ mm}$,

$\phi = \pi/2 \text{ radians}$,

$R = -D/2$,

$cb' = 0.307 \text{ mm}$, and

$$\tau_{s \text{ max}} = 58580T, \quad (A-7)$$

where

$\tau_{s \text{ max}}$ is given in MPa, and T is expressed in N·m.

(The concave situation of boundary requires that $-R$ be used in the formula.)

For an assumed yield strength for C2 carbide of 1930 MPa,

$$T_{\text{max allowed}} = \frac{\sigma_{\text{yield}}}{58580} = 0.0329 \text{ N·m}. \quad (A-8)$$

BORE-SIZE DRILL

Using the same approach as above for the bore-size drill, with the exception of using cb' for an irregular polygon of straight sides,

where

$$cb' = \frac{Di}{\left(\frac{1 + \pi^2 Di^4}{16A^2}\right)} \left[1 + 0.015 \left(\frac{\pi^2 Di^4}{16A^2} - \frac{Di}{2R} \right) \right], \quad (A-9)$$

and $R = +\infty$,

$$cb' = 0.242 \text{ mm}, \quad (A-10)$$

$$\tau_{s \text{ max}} = 99460T,$$

where

$\tau_{s \text{ max}}$ is given in MPa, and T is expressed in N·m.

$$T_{\text{max allowed}} = 0.0193 \text{ N·m}.$$

CIRCUIT BOARD DRILL, SPIRAL-FLUTE PIVOT DRILL, AND TWIST DRILL

Using Equations A-4 through A-6, and the values in Table 8, the calculated values for cb' , shearing stress, and maximum allowable torque are given in Table A-1.

Table A-1. Calculated Strengths of Drills

Drill	Inscribed Diameter (mm)	PHi (Degrees)	cb' (mm)	Shear Stress* (MPa)	Maximum Allowed Torque (N·m)
Printed Circuit Board	0.284	95	0.30	98852T	0.220
Bore- Size	0.272	95	0.24	99460T	0.019
Spiral- Pivot	0.307	120	0.34	65902T	0.452
Master	0.300	90	0.31	58580T	0.033
Flat- Pivot	Not required	NA	NA		0.026
Standard Twist	0.307	115	0.30	100073T	0.030

*Shear stress = indicated value in MPa times torque in N·m.

Appendix B

APPROXIMATE CUTTING SPEEDS AND FEEDS
RECOMMENDED FOR STANDARD TWIST DRILLS

Table B-1. Approximate Cutting Speeds and Feeds Recommended
for Standard Twist Drills*

Material	Feedrate ($\mu\text{m}/\text{rev}$)	Drill Diameter (mm)
Free Cutting Brass. Use maximum spindle speed available on machine.	43.2	0.50
	61.0	1.00
	121.9	1.59
	182.9	2.38
	279.4	3.18
2011-ST Aluminum (4.1 m/s).	30.5	0.50
	43.2	1.00
	63.5	1.59
	78.7	2.38
	111.8	3.18
2017-ST Aluminum and 5053-ST Aluminum (2.8 m/s).	27.9	0.50
	38.1	1.00
	55.9	1.59
	68.6	2.38
	96.5	3.18
2024-ST Aluminum (2.0 m/s); 6061 Aluminum (Naval Brass) (1 m/s); Copper (Tobin Bronze) (1.5 m/s).	25.4	0.50
	35.6	1.00
	50.8	1.59
	63.5	2.38
	88.9	3.18
High Sulphur Steel (B-1113) (X-1112) (B & S 12A) (1.15 m/s); (C-1113) (1.0 m/s); (B-1112) (0.84 m/s).	22.9	0.50
	30.5	1.00
	43.2	1.59
	53.3	2.38
	76.2	3.18
Type 416 and 430F Stainless Steel (0.66 m/s).	22.9	0.50
	30.5	1.00
	45.7	1.59
	55.9	2.38
	78.7	3.18

Table B-1 Continued. Approximate Cutting Speeds and Feeds
Recommended for Standard Twist Drills*

Material	Feedrate ($\mu\text{m}/\text{rev}$)	Drill Diameter (mm)
Steels Rated at 0.57 m/s.	20.3	0.50
	27.9	1.00
	40.6	1.59
	50.8	2.38
	68.6	3.18
Steels Rated at 0.48 m/s.	17.8	0.50
	22.9	1.00
	35.6	1.59
	45.7	2.38
	61.0	3.18
All Other Stainless Steels. Tool Steel (0.38 m/s); Monel (0.31 m/s); Phosphor A, B, and D Bronze and HS Steel (0.33 m/s).	15.2	0.50
	20.3	1.00
	30.5	1.59
	40.6	2.38
	50.8	3.18
*From Reference 3.		

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Miniature components for precision electro-mechanical mechanisms such as switches, timers, and actuators typically require a number of small holes. Due to precision, materials, and part geometry, most holes are produced by conventional drilling techniques. Such techniques are tedious and often require trial and error to prevent drill breakage, and to minimize hole mislocation and hole diameter variations. An initial study of drill geometries and drill techniques to produce 0.66-mm-diameter holes in stainless

MECHANICAL: Drilling Miniature Holes

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steel and brass indicates that positional tolerances of $50.8 \mu\text{m}$ can be maintained. With appropriate drills, a repeatability of $\pm 2.54 \mu\text{m}$ can be maintained. An analysis of the strengths and deflection characteristics of the eight drills utilized in this study indicated that the printed circuit board drills and the spiral-flute pivot drills had the most rigid features. This is consistent with the tests of locational and size accuracy. Drills of this size can be fed at feedrates of $25.4 \mu\text{m}/\text{revolution}$ in brass and stainless steel without breaking. Once the drill point starts into the workpiece, the elastic stability of the drill is not a major factor in breakage.

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