DRILLING MINIATURE HOLES, PART III

BDX-613-1787 (Rev.)

Published July 1978

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Topical Report

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DRILLING MINIATURE HOLES, PART III

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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. Because of the precision required, the workpiece materials, and the geometry of the parts, most of these holes must be produced by conventional drilling techniques. The use of such techniques is tedious and often requires considerable trial and error to prevent drill breakage, minimize hole mislocation and variations in hole diameter.

This study of eight commercial drill designs revealed that printed circuit board drills produced better locational and size repeatability than did other drills when centerdrilling was not used. Boring holes 1 mm in diameter, or less, as a general rule did not improve hole location in brass or stainless steel. Hole locations of patterns of 0.66-mm holes can be maintained within 25.4- μ m diametral positional tolerance if setup misalignments can be eliminated. Size tolerances of $\pm 3.8 \mu$ m can be maintained under some conditions when drilling flat plates. While these levels of precision are possible with existing off-the-shelf drills, they may not be practical in many cases.

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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 utilized. These approaches are tedious and require great care to prevent drill breakage and 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.

The results of this study in 303Se stainless steel and half hard brass are summarized in the following observations for 0.66-mm-diameter drills.

- When centerdrilling was not used, printed circuit board drills, spiral-flute pivot drills, and bore-size drills produced distinctly more consistent size and location than the other drills studied.
- Feedrate did not influence hole location except for some drills in brass workpieces.
- Centerdrilling as a general rule dramatically improved hole locations when chisel-point drills were used but had no effect when printed circuit board drills were used.
- There was little difference in the locational accuracy of the new eight spindle drilling machine and the N/C jig borer.
- Boring holes did not improve hole location.
- When drilling was performed without prior or subsequent operations, the holes tended to be 6 μm larger than the drill in stainless steel. Reaming reduced this oversizing effect to near zero in some tests.
- Of all the conditions studied, half resulted in hole patterns positioned within 31 μm . Under the best conditions a diametral positional tolerance of 11.20 μm was maintained.
- Of all the conditions studied, half resulted in a repeatability of hole size of 31 μm . Under the best conditions, a size repeatability of 9.60 μm was maintained.
- The most repeatable drill when both size and location had to be maintained was the printed circuit board drill.

- The drill is the least expensive of all the factors which contribute to drilling cost. Setup time is typically the most expensive factor when producing precision holes in small lot sizes.
- A chip clearing (pecking) operation may influence hole location unless centerdrilling is used.
- Spindle speed did not affect hole size or location.
- Some combinations of feedrate, technique, and drill geometry were distinctly better or worse than others. (The best combination of feedrate and drilling technique may be different for each drill.)

The feedrates used ranged from 2.5 to 12.5 $\mu\text{m}/\text{rev}$, and the spindle speeds ranged from 2200 to 6800 RPM.

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. Specifically, the study evaluated the effects of several types of drilling machines and tooling and the effects of drill geometry, feeds, and speeds.

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 0.75 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 phase utilized a single machine to evaluate the basic capabilities of eight different drill configurations. In this phase, only one hole was produced in each specimen.

In the second phase, analytical and empirical analyses were made of drill rigidity and its effect on hole location and size consistency. Typical drilling torques and thrusts were also evaluated and compared to hole location and size trends.

In the third phase, patterns of holes were drilled with the more successful drills from 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 amount of observations made, this study is reported in three parts, with each part corresponding to the phases just described. This third report includes the final conclusions of this study. The following list describes in more detail the emphasis in each part of this study.

Study Objectives

Pertinent Part of Report

- To determine the effects of speed and feed on small hole location and quality. Part 1 (BDX-613-1785)¹
- To determine which drill geometries and techniques produce the minimum hole size and location variance. Parts 1 and 2 (BDX-613-1785¹ and BDX-613-1786²)
- To determine the relative abilities of the following two techniques for maintaining 7.6 μm total size tolerance while producing holes 0.25 to 0.76 mm in diameter to positional tolerances of 25.4 μm RFS, and interior surface finishes of 0.45 μm AA. Part 3 (BDX-613-1787)
 1. N/C Jig Bore
 2. N/C Eight Spindle Drill

Multiple Hole Tests

Test Approach

The purpose of the multiple hole tests was to verify that the results of the single hole tests produced on a template controlled duplicator drilling machine¹ accurately indicated what could be expected on precision production equipment. Whereas the duplicator drill may be able to maintain 50 μm locational tolerance on a single hole pattern, there is no reason to believe that it can hold a 25 μm positional tolerance on each hole in a pattern of holes. The N/C drills and jig borers which are usually used for precision small holes also have structural differences which could make the results from other machines inapplicable. In other words, the best drills for one machine may not be the best choices for another.

The machine combinations studied in this phase were an N/C Jig Bore, and an N/C eight spindle drilling machine.

The rationale for investigating the N/C drilling machine is that its eight spindles make it roughly 20 percent faster to use than single-spindle jig borers, although it is not inherently as accurate as a jig borer.

An intended study of using a drill guide plate in conjunction with the eight spindle drill was not pursued in any depth because of

uncontrollable drill breakage. The attempted use of carbide drills in a conventional drill jig also produced the same results.

An eight-hole pattern, such as that shown in Figure 1, was produced in two plates of 1.5-mm-thick alloy 6 brass and 302 stainless steel. A downfeed of $7.6 \mu\text{m}/\text{rev}$ and a spindle speed of 3600 RPM were used for the holes produced on the eight spindle drill. The N/C jig borer was handfed rather than machinefed. No drill clearing (pecking) was used. A total number of holes produced in this phase of the study was 560.

Both sides of the drilled holes were deburred in an attempt to maintain $76.2\text{-}\mu\text{m}$ maximum edge break. The holes were ultrasonically cleaned and airblown dry. The hole locations and size were inspected to the nearest $2.54 \mu\text{m}$. Hole size was inspected with Deltronic size wires, and locations were measured with a Zeiss Coordinate Measuring Machine.

The hole size data were analyzed for

- Difference between hole size and drill size, and
- Repeatability of hole size.

The initial drill size was used as the baseline for all difference measurements, since drill wear was not expected to be measurable. All drills produced 16 holes.

Hole location data were analyzed for locational repeatability and average mislocation. This analysis was performed by using a computer routine known as "Tramper," from Sandia Laboratories, Albuquerque. This program translates and rotates X, Y data for hole patterns in an attempt to remove mislocation errors caused by machine tool and setup biases. The net result is a series of values of the repeatability of hole location after these biases have been removed. The data displayed in this report are *radial* mislocation.

The rationale for this approach is that by trial and error, or by utilizing positioning feedback information, it is possible to eliminate all of these biases. Since drilling repeatability rather than setup-type errors was investigated in this study, it is important to eliminate these biases from the analysis.

For each series of data from two plates, three statistical tests were performed. Bartlett's test was performed to determine if any difference existed between variances on plates. A chi square test was performed to determine if there was any significant difference between the hole accuracies on an individual plate. An "F" ratio test for pooled variance was performed to determine if group averages between plates machined the same way were different.

Table 1. Identification of Processes Used

Process Number	Process Description	Workpiece Material	Specimen Numbers	Machine Used
1	Centerdrill, No. 9 point, bore, ream	Brass Stainless Steel		Eight Spindle Drill
2	Centerdrill, No. 9 point, drill, ream	Brass Stainless Steel	27, 28 1, 2	
3	No. 9 point drill, ream	Brass Stainless Steel	29, 30 3, 4	
4	No. 9 point drill	Brass Stainless Steel	31, 32 5, 6	
5	Centerdrill, No. 9 point drill	Brass Stainless Steel	34, 35 7, 8	
6	GHD drill	Brass Stainless Steel	36, 37 9, 10	
7	Centerdrill, GHD drill	Brass Stainless Steel	38, 39 11, 12	
8	Chisel-point drill	Brass Stainless Steel	40, 41 23, 24	
9	Centerdrill, chisel-point drill	Brass Stainless Steel	33, 48 21, 22	
10	Bore-size drill	Brass Stainless Steel	42, 43 19, 20	
11	Centerdrill, bore-size drill	Brass Stainless Steel	49, 72 17, 18	Eight Spindle Drill

Table 1 Continued. Identification of Processes Used

Process Number	Process Description	Workpiece Material	Specimen Numbers	Machine Used
12	Spiral-flute pivot drill	Brass Stainless Steel	46, 47 15, 16	Eight Spindle Drill
13	Centerdrill, sprial-flute pivot drill	Brass Stainless Steel	44, 45 13, 14	Eight Spindle Drill
14	Centerdrill, No. 9 point drill, bore, ream	Brass Stainless Steel	50, 59 60, 71	N/C Jig Borer
15	Centerdrill, No. 9 point drill, ream	Brass Stainless Steel	69, 70	N/C Jig Borer
16	No. 9 point drill, ream	Brass Stainless Steel	54, 57 63, 64	
17	No. 9 point drill	Brass Stainless Steel	53, 55 61, 62	
18	Centerdrill, No. 9 point drill	Brass Stainless Steel	51, 52 67, 68	
Note: No. 9 point refers to a standard four-facet point (Drill 48701022). GHD refers to gold-head drill.				

Table 2. Ranking of Hole Production Techniques for Hole Location Repeatability in Brass Workpieces

Rank	Process Number	Positional Tolerance* (μm)
1	17	11.20
2	2	12.37
3	3	17.60
4	9	18.92
5	15	19.71
6	4	19.96
7	6	21.74
8	13	25.93
9	11	29.46
10	16	31.32
11	1	34.26
12	14	39.94
13	7	42.47
14	18	50.47
15	5	63.22
16	10	74.12
17	12	118.36
18	8	1698.75

*Expressed as diametral tolerance (that is, process number 2 hole locations in brass all fell within a locational tolerance of 12.37 μm diameter).

Table 3. Ranking of Hole Production Techniques for Hole Location in Stainless Steel Workpieces

Rank	Process Number	Positional Tolerance* (μm)
1	9	11.76
2	14	16.18
3	5	23.01
4	18	24.56
5	15	26.95
6	3	27.10
7	16	27.46
8	2	27.66
9	4	44.22
10	7	49.12
11	13	51.21
12	10	58.27
13	11	69.62
14	12	92.33
15	6	100.51
16	8	187.76
17	17	2888.23
18	**	

*Expressed as diametral tolerance (that is, process number 2 hole locations in brass all fell within a locational tolerance of 27.66 μm diameter).

**Process 1 was not performed on these parts.

Table 4. Ranking of Hole Production Techniques for Average Hole Size Differences in Brass Workpieces

Rank	Process Number	Average Size Difference* (μm)
1	2	-0.33
2	4	0.64
3	16	0.84
4	5	1.12
5	3	4.29
6	12	5.72
7	17	8.89
8	13	9.22
9	7	9.53
10	14	10.16
11	18	11.76
12	9	12.07
13	6	16.51
14	10	22.56
15	11	23.50
16	8	35.89
17	1	49.53
18	15	80.01

*Size difference is the hole size minus the drill diameter. A negative size indicates that the hole was smaller than the initial drill diameter.

Table 5. Ranking of Hole Production Techniques for Average Hole Size Differences in Stainless Steel Workpieces

Rank	Process Number	Average Size Difference* (μm)
1	2	0
2	15	-1.12
3	18	-1.12
4	14	1.45
5	12	3.18
6	3	3.18
7	17	3.38
8	16	3.81
9	13	6.50
10	4	7.14
11	6	8.41
12	7	9.68
13	8	10.95
14	5	13.97
15	9	17.78
16	10	21.29
17	11	21.44
18	**	

*Size difference is the hole size minus the drill diameter. A negative size indicates that the hole was smaller than the initial drill diameter.

**Process number 1 was not included in this study.

Table 6. Ranking of Hole Production Techniques for Hole Size Repeatability in Brass Workpieces

Rank	Process Number	Hole Size Repeatability* (μm)
1	11	10.82
2	15	10.82
3	10	13.41
4	13	15.54
5	2	19.96
6	12	21.18
7	7	21.95
8	6	28.35
9	4	30.78
10	9	31.24
11	16	35.36
12	1	35.51
13	17	36.88
14	3	39.62
15	14	43.59
16	5	46.18
17	18	56.69
18	8	87.17

*This value is $\pm 3\sigma$ of hole sizes from 16 holes.

In evaluating the results of this test, it is important to understand thoroughly the various standard deviations one can obtain when analyzing hole pattern data.

Figure 2 illustrates an arbitrary four-hole pattern of desired hole locations ("+" sign), and actual hole positions on two separate parts (dots and circles). If one calculates the standard deviation of any single set of holes from their desired location,

Table 7. Ranking of Hole Production Techniques for Hole Size Repeatability in Stainless Steel Workpieces

Rank	Process Number	Hole Size Repeatability* (μm)
1	16	9.60
2	13	9.60
3	18	11.13
4	10	18.29
5	3	19.66
6	12	24.54
7	4	27.89
8	15	32.46
9	7	36.58
10	14	39.93
11	2	40.08
12	17	46.63
13	11	47.55
14	6	50.60
15	9	67.67
16	8	69.65
17	5	126.95
18	**	

*This value is $\pm 3\sigma$ of hole sizes from 16 holes.

**Process #1 was not performed in this test.

σ_{R_A} will result. This will provide the standard deviation one needs to determine the diametral positional tolerance one needs on the part drawing to accept this group of parts. If the variances of each of the four-hole clusters are pooled, one can obtain the

Table 8. Ranking of Hole Production Techniques for Hole Location and Size Repeatability for Brass Workpieces

Rank	Process Number	Locational Accuracy x Size Repeatability (μm^2)
1	15	213
2	2	247
3	11	319
4	13	403
5	17	413
6	9	591
7	4	614
8	6	616
9	3	697
10	7	932
11	10	994
12	16	1,109
13	1	1,216
14	14	1,727
15	12	2,507
16	18	2,861
17	5	2,920
18	8	148,015

diametral positional tolerance $\sigma_{R_{Ap}}$ required on the part drawing to accept the four-hole pattern.

In Appendix A, it is shown that a radial standard deviation can be approximated by

Table 9. Ranking of Hole Production Techniques for Hole Location and Size Repeatability for Stainless Steel Workpieces

Rank	Process Number	Locational Accuracy x Size Repeatability (μm^2)
1	16	264
2	18	273
3	13	492
4	3	533
5	14	646
6	7	699
7	9	796
8	15	875
9	10	1,066
10	2	1,109
11	4	1,233
12	12	2,266
13	5	2,920
14	11	3,310
15	6	5,086
16	8	13,077
17	17	134,667

$$\sigma_r = \left[\frac{\bar{x}^2 \sigma_x^2 + \bar{y}^2 \sigma_y^2}{\bar{X}^2 + \bar{Y}^2} \right]^{1/2}, \quad (1)$$

where

r = radius of any circle,

σ_r = radial standard deviation from the point $(\bar{X}, \bar{Y})$,

$\bar{X}$ = mean x direction hole mislocation,

$\bar{Y}$ = mean y direction hole mislocation,

σ_x = standard deviation of hole pattern in x direction, and

σ_y = standard deviation of hole pattern in y direction.

Equation 1 can apply to multiple holes at a single-hole position or to a pattern of holes in many parts.

Unfortunately, the data shown in Figure 2 include the following subcomponents of error:

- Cutting tool repeatability,
- Spindle and collet repeatability,
- Measuring error,
- Table positioning repeatability,
- Setup errors, and
- Bias between hole clusters.

The table or part positioning errors include the fact that there is always some mislocation of the hole pattern with respect to other datums on the part. This mislocation can be the result of setup errors or of repeatability limitations in placing each workpiece in the fixture in exactly the same manner as the previous parts. These positioning errors can essentially result in translation of the pattern or rotation of the pattern from the desired position.

Since this study was dedicated to investigating the capabilities of cutting tools (drills) and machine accuracies, it was essential to remove the setup errors. This was done by performing a least squares fit of each part to the desired hole locations. This was done by a Sandia developed computer program known as *Tramper*.

As shown in Figure 3, when this least squares program is used, the resulting standard deviation (σ_{rT}) is smaller than the initial

deviation (σ_{rA}). It is important to recognize, however, that in

performing this analysis it is assumed that only the hole pattern *repeatability* is significant, opposed to the repeatability of the holes to an exterior datum.

Figure 2. Pattern of Holes and Desired Hole Location

Figure 3. Pattern of Holes After Using Tramper Program

In the normal case of using N/C equipment, one would expect the transformed data to be uniformly distributed about the desired hole location. If, however, the N/C tape had gross errors in it, it would be possible after transformation to obtain a distribution such as that shown in Figure 4. In this case, the variation in hole location is not sufficient in itself to define the diametral tolerance required to produce these holes within tolerance, and the center of the hole pattern produced is offset from the desired center. This type of occurrence is typical of what one would find by using a drill jig in which the drill bushing centerlines were slightly different than the desired part hole centerlines. This bias in results is, however, not typical of the results found on N/C equipment.

Appendix C presents some step-by-step procedures for evaluating the various standard deviations and patterns discussed thus far.

The $3\sigma_{r_T}$ limit used in this section does not denote the same degree of probability as in rectangular coordinates. As an example, if³

$$\sigma_x = \sigma_y = \sigma, \quad (2)$$

then

$$P = 1 - e^{-r^2/2\sigma^2}, \quad (3)$$

where

P = probability of holes falling within a circle of radius r.

If we chose $r = 3\sigma$,

then

$$P = 1 - e^{-9/2} = 0.9889 \approx 0.99.$$

Thus, for this condition one would expect 99 percent of all holes drilled to fall within the 3σ radius.

By manipulating Equation 3, it is possible to obtain the following expression for radius as a function of probability.

$$r = \left[-2\sigma^2 \ln (1 - P) \right]^{1/2}. \quad (4)$$

By using Equations 2 and 4, one will find that 95 percent of the holes would fall within the radius 2.448σ .

Figure 4. Relative Relationship Between σ_{r_D} and σ_{r_T}

Unfortunately, much of the data did not meet the criteria that $\sigma_x = \sigma_y$ (Appendix Table B-1).

The data for hole location repeatability (Tables 2 and 3) indicate that under the very best conditions of perfect tool and machine alignment a true position diametral tolerance of $13.8 \mu\text{m}$ would be required on part drawings. A more realistic tolerance of $30.4 \mu\text{m}$ would be required if any of the *best half* of the combinations studied were used. It is significant that if the wrong drill and technique were used, a positional tolerance of $101.6 \mu\text{m}$ or greater would be needed just because of cutting tool nonrepeatability.

Figure 5 shows that when drilling was used without any center-drilling the Number 9 drill point (printed circuit board four-facet point) produced the most consistent results. When centerdrilling was used, the chisel-point drill proved to be the most consistent. There was no obvious difference between the results in brass and those in stainless steel except for some specific combinations.

Figure 6 illustrates that while differences did exist between the techniques used they did not make the major difference that was expected. Surprisingly, some of the results in brass were worse than those in stainless steel. One would have assumed that because drills typically have a difficult time getting started in stainless steel their location in stainless steel would suffer noticeably.

There also was little difference in the results produced by the jig borer and those produced by the eight spindle drill (Figures 7 and 8). Because the eight spindle drill uses a revolving turret with

Text continued on page 33.

Figure 5. Comparison of Hole Location Accuracy by Drill and Technique in Stainless Steel and Brass, Using Eight Spindle Drill

Figure 6. Comparison of Typical Best Techniques for Hole Location, Using a No. 9 Drill Point and a Chisel-Point Drill With an Eight Spindle Drilling Machine

Figure 7. Effect of Drilling Technique and Machine on Hole Location Accuracy in Brass, Using a No. 9 Drill Point

Figure 8. Effect of Drilling Technique and Machine on Hole Location Accuracy in Stainless Steel, Using a No. 9 Drill Point

eight different spindles, its accuracy and repeatability should be less than the precision single-spindle jig borer.

Average Hole Size. Tables 4 and 5 show the difference between hole size and initial tool size. As indicated, some holes were smaller than the tool which produced the hole. This can be the result of thermal expansion during machining as well as tool wear from the measured tool size and measuring error on either the tool or the hole.

Half of the holes measured were less than 10 μm larger than the tool (Tables 4 and 5). One hole production technique resulted in holes 80 μm larger than the final tool (Table 4).

There is little unanimity in the results from various drills, production techniques, or materials. Figure 9, for example, indicates that the Number 9 drill point produced holes closest to tool size in stainless steel, but the results in brass were erratic. There was little difference in the results produced in brass by the jig borer and the eight spindle drill except for the cases of centerdrilling, drilling, and reaming and the centerdrilling, drilling, boring, and reaming sequence (Figure 10). In stainless steel there was a significant difference in the centerdrilling and drilling sequence (Figure 11). There was little significant difference between the results produced by different drills except that the Number 9 drill point produced holes much closer to tool size than did the others (Figure 12).

Hole Size Repeatability. Under the very best circumstances for the conditions studied, a 10 μm variation in hole size will occur in a group of parts (Tables 6 and 7). If the wrong tool or technique are used, the hole size can vary by 127 μm . For the conditions used in this study, at least a 25.4 μm tolerance would be required on hole size in order to use the best 30 percent of hole production techniques studied.

With the exception of centerdrilling and drilling in stainless steel, there was no significant difference in the repeatability of holes produced by the jig borer or the eight spindle drill (Figures 13 and 14). There was little real difference between drilling techniques when the Number 9 drill point was used (Figures 13 and 14). The chisel-point drill resulted in slightly less repeatable hole size than did the Number 9 drill point (Figure 15). The bore-size drill produced the most consistent hole size (Figure 16). The spiral-flute pivot drill was also very consistent.

Hole Quality Index. In any production situation, the requirement for holes is that they meet size and location specifications on a repeatable basis. As a result, techniques which produce a repeatable size but not a repeatable location are unacceptable. To

Figure 9. Comparison of Typically Best Techniques for Hole Size, Using an SIP Jig Bore Machine for No. 9 Drill Point Tests, and an Eight Spindle Drilling Machine for Chisel-Point Drill Tests

Figure 10. Effect of Drilling Technique and Machine on Hole Size Difference in Brass, Using a No. 9 Drill Point

Figure 11. Effect of Drilling Technique and Machine on Hole Size Difference in Stainless Steel, Using a No. 9 Drill Point

Figure 12. Average Hole Oversize by Drill and Technique in Brass and Stainless Steel

Figure 13. Effect of Drilling Technique and Machine on Hole-Size Repeatability in Brass, Using a No. 9 Drill Point

provide some figure of merit or hole quality index that classifies a technique by both these aspects the locational repeatability and size repeatability of each combination were multiplied together. This resulted in the ranking shown in Tables 8 and 9.

As shown in these tables, there is a major difference between the capabilities of techniques studied. Unfortunately, for brass workpieces it is impossible to discern a pattern in the results. In stainless steel, five of the best six combinations utilized the Number 9 drill point, and four of these five utilized the jig borer.

Text continued on page 42.

Figure 14. Effect of Drilling Technique and Machine on Hole Size Repeatability in Stainless Steel, Using a No. 9 Drill Point

Figure 15. Comparison of Typical Best Techniques for Hole Size Repeatability, Using a Jig Bore for No. 9 Drill Point Tests, and an Eight Spindle Drilling Machine for Chisel-Point Drill Tests

Figure 16. Comparison of Hole-Size Repeatability by Drill and Technique in Stainless Steel and Brass

Implications of Study

In summarizing the results of this test, the following conclusions became apparent.

- Patterns of holes can be produced within a tolerance of 25.4 μm diametral true position by commercial off-the-shelf drills.
- In some instances, it is possible to produce holes which are smaller than the initial drill size.
- As a typical rule, holes were 2.54 to 10.16 μm larger on the average than the hole sizing tool.
- Hole sizes typically varied from ± 5.08 to ± 15.24 μm from the average oversize. In no case was the $\pm 3\sigma$ range less than ± 5.08 μm .
- As a general rule, the four-facet (printed circuit board or Number 9) drill point produced both better size and location repeatability than did the other drills.
- The chisel-point drill cannot be used for precision work without centerdrilling prior to drilling.
- While centerdrilling generally improved hole location and size repeatability, in some instances it resulted in worse performance.
- The combination of centerdrilling, drilling, and reaming produced the smallest difference between average hole size and tool size, and in brass it resulted in the most consistent hole size.
- Boring the hole did *not* improve hole accuracy.
- As a general rule, there was no significant difference between the accuracy of the eight-spindle drilling machine and the jig borer.

It is important to recognize that this study was dedicated to determining the optimum consistency one could obtain from a number of drills, using conventional drilling equipment. The fact that holes can be produced to a positional accuracy of 25.4 μm true position diameter should be considered carefully. This capability may not exist in other materials, or other equipment, or with another manufacturer's drills. The fact that it did occur in this test, however, indicates that this high level of accuracy can be achieved.

It is also significant to note that the statistical technique used in this study assumes that the workpiece and fixturing can be adjusted in such a way that *all* setup errors are removed. This is not always feasible, but in precision applications it is mandatory.

Measurement Repeatability

The hole location data presented in this study also includes some measurement error. Because most of the calculated standard deviations were small, it is assumed that the measurement error or repeatability is also small. Throughout this study, hole location measurements were recorded to the nearest 2.54 μm . On equipment available today even finer discrimination is available. Separate tests of measurement repeatability on the Zeiss measuring machine indicate that a standard deviation of 1.524 μm is typical of this equipment. While this is small, it is still significant when compared to some of the values listed in Appendix Table B-1. Assuming no correlation exists between measuring error and the calculated repeatability, σ_{r_T} , one can obtain a closer estimate of the real σ_{r_T} from the following equation.

$$\sigma_{r_T} \text{ actual} = \left(\sigma_{r_T}^2 \text{ calculated} - \sigma^2 \text{ measurement} \right)^{1/2} \quad (5)$$

The use of size wires to measure hole size does not allow one to characterize hole roundness, bell mouthing, or any of the other characteristics of size. In addition, it is possible to slightly increase hole size during the measuring process. Unfortunately, no better technique is available to measure functional size on holes this size.

Comparisons With Phase I and Phase II Results

Comparisons between the Phase I and Phase III results do not reveal any gross differences on hole location in brass parts with the exception of the spiral-flute pivot drill and the chisel-point drill (Table 10). In both instances, the Phase III results indicated less repeatability by at least a factor of 3.0. The major source of difference is probably the higher feedrates used in Phase III. In stainless steel, no major locational differences were observed (Table 11).

In brass workpieces, the difference between measured hole size and measured tool size was typically smaller for the Phase III tests. The gold-head drill was an exception to this trend (Table 10). In stainless steel, the Number 9 drill point and the

Text continued on page 48.

Table 10. Comparisons Between Phase I and III Results in Brass*

Drill Used	Technique	Hole Feature					
		Location (μm)		Size (μm)		Size (μm)	
		(I)	(III)	(I)	(III)	(I)	(III)
No. 9 Point	Drill only Centerdrill, Drill	6.350	3.302	-1.016	0.6350	0.254	5.080
			10.414				7.620
Bore-Size	Drill only Centerdrill, Drill	14.224	12.466	25.654	22.5552	1.016	2.286
			4.826				1.778
Spiral-Flute	Drill only Centerdrill, Drill	6.604	19.812	8.128	5.7150	1.016	3.556
			4.318				2.540
Gold-Head	Drill only Centerdrill, Drill	3.556	3.556	-2.286	16.5100	3.048	4.826
			7.112				3.556
Master Drill	Drill only Centerdrill, Drill	12.700	---*	25.908	---	2.794	---
			---				---
Flat-Pivot	Drill only Centerdrill, Drill	9.652	---	24.892	---	2.032	---
			---				---

Table 10. Continued. Comparisons Between Phase I and III Results in Brass*

Drill Used	Technique	Hole Feature					
		Location (μm)		Size (μm)		Size (μm)	
		(I)	(III)	(I)	(III)	(I)	(III)
Chisel-Point	Drill only	13.970	288.290	7.366	35.8902	1.270	14.478
	Centerdrill, Drill		3.302		12.0650		5.334

*Data for Phase I based on data averaged over centerdrilled and drilled holes and two feedrates.

**Dashes indicate that no measurements were made under those conditions.

Table 11. Comparisons Between Phase I and Phase III Results in Stainless Steel*

Drill Used	Technique	Hole Feature					
		Location σ (μm)		Size (μm)		Size σ (μm)	
		(I)	(III)	(I)	(III)	(I)	(III)
No. 9 Point	Drill only Centerdrill, Drill	11.176	7.366	-1.778	5.080	0.5588	4.572
			3.810		13.970		21.082
Bore-Size	Drill only Centerdrill, Drill	10.160	9.652	3.048	10.160	0.7366	3.048
			11.684		21.336		8.128
Sprial-Flute Pivot	Drill only Centerdrill, Drill	11.684	15.494	2.286	3.048	0.8636	4.064
			8.382		6.604		1.524
Gold-Head	Drill only Centerdrill, Drill	19.558	16.764	19.050	8.382	3.6322	8.382
			8.128		9.652		6.096
Master Drill	Drill only Centerdrill, Drill	19.050	---**	23.114	---	3.9116	---
			---		---		---
Flat-Pivot	Drill only Centerdrill, Drill	26.670	---	21.082	---	4.9784	---
			---		---		---

Table 11. Continued. Comparisons Between Phase I and Phase III Results in Stainless Steel*

Drill Used	Technique	Hole Feature					
		Location σ (μm)		Size (μm)		Size σ (μm)	
		(I)	(III)	(I)	(III)	(I)	(III)
Chisel-Point	Drill only	---	31.242	---	10.922	---	11.684
	Centerdrill, Drill		3.302		17.780		11.176

*Data for Phase I based on average data for centerdrilling, and not centerdrilling and slow and fast feedrates.

**Dashes indicate that no measurements were made under those conditions.

bore-size drill produced significantly larger average size results for Phase III tests than for Phase I results (Table 11).

In every case, the repeatability of hole size was less in the Phase III tests than in the Phase I tests. This appears to be a direct result of faster feedrates, larger sampling population, and difference in measuring technique. From a production standpoint, the Phase III results are more realistic although the Phase I results do indicate actual process potential capabilities.

As indicated in an earlier report,² drill performance is in large part controlled by such drill parameters as the following:

- Modulus of elasticity,
- Flute length,
- Cross-sectional area,
- Helix angle,
- Cutting edge sharpness, and
- Drill point configuration.

In most materials, the carbide drills will deflect less than high-speed steel drills because carbide is three times stiffer. As indicated by Oxford,^{4,5} increasing drill length decreases drill stiffness tremendously. In one example, a 40-percent reduction in flute length increased drill life 8000 percent. Savage⁶ found similar but less dramatic results on locational repeatability. Garina⁷ has noted that the deflection mode of drills changes as length increases which, in turn, will affect accuracy but less consistently than traditional theory might indicate.

The result of Oxford's studies indicates that drill rigidity can be calculated, but its locational performance has not been analytically related to rigidity. From elementary strength of materials, however, one can assume that locational repeatability is proportional to the term

$$\sigma \propto \frac{EI}{L^3}, \quad (6)$$

where

E is the modulus of elasticity,

I is the cross sectional moment of inertia, and

L is the flute length.

As Oxford^{4,5} indicates, the diameter of a circle d_i , which can be inscribed within the boundaries of the drill cross¹ section, is a good measure of the inertia or section modulus (Figures 17 and 18) of the drill cross section. Thus, for a given drill point the drill having the least deviation on hole location should have the highest possible value of EI/L^3 .

Drill point configuration plays a major role in determining accuracy of hole location.^{8,9} For many years it has been industry practice to centerdrill before drilling in order to keep chisel-point drills from *walking off* the desired location. Figure 6 illustrates vividly the penalty one pays if centerdrilling is not utilized with this drill.

The nominal point configuration is not the only point factor, however, which influences hole location and size repeatability. The difference in lip heights (Figure 19) on a drill can greatly affect repeatability and average hole size.⁸ Unfortunately, commercial drills frequently have lip height differences up to 50.8 μm even on small drills. This is a large enough difference to greatly deflect a drill of the size used in this study.

From a production standpoint, this factor is the most difficult to control since it varies on every drill purchased. At the present time, control of lip height differences can only be controlled in most companies by inspecting every drill point and discarding those with differences greater than 12.7 or 25.4 μm .

Helix angle, drill-point angle, and rake and clearance angles also can greatly affect hole quality.^{8,10,11} Oxford's work provides part of the reason for these effects. The effect of helix angle on rigidity can also be appreciated from Fujii, DeVries, and Wu's work.¹² These factors were not evaluated in the present study, however.

While spindle speed and feedrate effects were not studied in this phase, there is little to suggest that speed would affect location or size. In Phase I¹ neither speed nor feed affected the location or size of holes produced by the master drill. In brass workpieces, the combination of feedrate and some hole production techniques did result in better or worse hole location. As indicated in Phase II results,² spindle speeds would have to approach 1,000,000 RPM before the drills used in this study would experience rotational stability problems.

When drilling is used without centerdrilling, the spiral-point pivot drill, the gold-head drill, the flat pivot drill, and the chisel-point drill did exhibit greater hole mislocation at high feedrates than at low feedrates.¹ Since all of the drills essentially have some chisel edge, it is not surprising that they

GENERAL PURPOSE DRILL

HEAVY DUTY DRILL

Figure 17. Transverse Cross Sections Through Typical Drill Flutes, Showing Inscribed Circles Used for Rigidity Analyses for General Purpose and Heavy Duty Drills

would tend to wander. As shown by torque and thrust data,² faster feedrates increase the cutting forces which, in turn, increase the possibility of initial hole mislocation. In-house production, experience also reflects the fact that chisel-point tools wander more at high feedrates if centerdrilling is not used.

One interesting sidelight to this study is that five individuals familiar with in-house drilling of small holes were asked to recommend the best drilling speed for 300 series stainless steel and four drill diameters. The recommendations for a 0.62 mm-diameter drill ranged from 430 to 4500 RPM. No two individuals agreed on the best speed. This same lack of agreement is strongly evident in the literature. There is a very wide range of recommended practice in the literature, in which one author has said that it is impossible to drill at a certain speed, feed, and drill size; and another author has said that these are the optimum conditions. Some of this lack of agreement appears to be the result of experience limited to a few conditions of the following many variables which influence hole drilling success. It is easy to visualize that two individuals might never see the same two sets of drilling conditions in practice.

Figure 18. Effect on Drill Rigidity of Inscribed-Diameter-to-Drill-Diameter Ratio (After Oxford⁴)

Figure 19. Lip Height Difference

Factors which control hole drilling success:

Drill point geometry,

Drill sharpness,

Clearance angles and lands,

Flute length,

Drill material,

Helix angle,

Equipment precision,

Hole location tolerance,

Hole size tolerance,

Depth of hole,

Hole diameter,

Chip packing,

Feedrate (and consistency),

Workpiece material, and

Workpiece heat-treat condition.

One of the few exceptions to consistency in recommended drilling practice is that recommended for use on automatic screw machines. As indicated in reference 1, in-house practice on screw machines is consistent with the limits of the equipment used, although feedrates are half those recommended by the manufacturer of at least one screw machine.

In-House Production Experience

In-house experience on automatic screw machines indicates that a hole size tolerance of $5.08 \mu\text{m}$ can be maintained in brass and stainless steel by centerdrilling, drilling, and reaming. Only 5 of 35 combinations analyzed in this Phase III study came close to maintaining this tolerance (Tables 6 and 7). Only two of these five combinations utilized reaming. Experience with special-design, multi-spindle boring heads also indicates that a $\pm 5.08 \mu\text{m}$ tolerance can be maintained on hole size.

There is some reason to believe that $\pm 3.81 \mu\text{m}$ size tolerance can be maintained for holes two diameters deep if large quantities can be produced in a single setup and if special reamers, *reamers*, or *microsizer*-type tools are used.

A review of parts made in-house in 1972 indicated that Bendix had requirements for 41 parts with locational tolerances of 25.4 to $72.2 \mu\text{m}$. These brass and stainless steel parts which precipitated this study had hole size tolerances of $\pm 3.8 \mu\text{m}$. These holes were typically 1 to 3 diameters deep, although some were 6 diameters deep. While the majority of these holes were single holes in pieceparts, 25 percent were part of a hole pattern.

The experience gained on production parts since that time indicates that a $50.8 \mu\text{m}$ location tolerance can be maintained with reasonable care and effort on many parts, but $25.4 \mu\text{m}$ was not a practical tolerance on most parts because of the many limitations in obtaining consistent tools. In addition, some hole variation always exists because of limitations in obtaining a perfect setup.

In most instances, the practice of boring small holes to obtain better locational accuracy has been abandoned on holes 1 mm or smaller. No commercial boring tool in this size range has the stiffness required to prevent tool deflection. If a hole is

initially mislocated slightly, it will continue to be off location after boring because of this fact. This in general is consistent with the results of this study.

Production reaming of small holes in 300 series stainless steel is typically a problem because of the work-hardening nature of this material. Reamers seize and break in this material if too little stock is removed, and if the chip load is too big they twist and break. A reasonable compromise in chip load is very difficult to obtain in this size range. Despite the availability of reamers in these sizes, most in-house production operators have experienced more success with the spiral-flute pivot drills on screw machines and printed circuit board drills on flat plates than with reamers. Fortunately, the printed circuit board drills produced by some manufacturers have excellent size repeatability within a group of drills.

Results of Literature and User Surveys

Sixty-five articles on small-hole drilling were reviewed before this study began. These references are listed in the bibliography of reference 1. As shown in the following list, these articles cite 31 innovations used to improve hole drilling or hole consistency. Unfortunately, at present there is no convenient method for analyzing the relative quantitative improvement that can be obtained by these innovations.

Innovations Cited in the Literature to Improve Hole Drilling or Hole Consistency

- Special Design Drilling Machines

- Fluid drive collets

- Fluid drive spindles

- Equipment dedicated specifically to miniature drills

- Ultra-precision equipment

- Tool and part rotation

- V-Block collets

- Belt drive spindles

- Automatic feed/speed cycle

- Computerized control of forces

- Using target dots to sense location

Cam feed/pneumatic feed/hydraulic feed/screw feed

Horizontal and upside down spindles

Constant thrust feed

- Special Tool Designs

Precision tolerances

Elastic coupling to shank

Special flute configurations

Shorter flutes

Increased back taper

Special point geometries (modified radial lip, crankshaft, and so forth)

High lip clearance angles

Special heat treatments

- Special Techniques

Noise sensors for determining initial contact and drilling problems

Intentionally bending the drill in machine for better alignment

Cooling plastic workpieces

Using chip clearing action

Sensing forces

Using coolants such as CCL_4

Varying workpiece constituents

Lapping for sizing and finishing

Refrigerating drills prior to use

Adding axial vibration to break up chips

Thirty-five manufacturers or users of small drills were also contacted during this study to obtain additional concepts for

improving hole quality. As also noted in the published literature, no two of these companies made the same recommendation. As an example, for drilling 0.25 mm-diameter holes, knowledgeable users recommended spindle speeds of 200 to 250,000 RPM. Seven companies recommended seven different coolants as being optimum.

Some companies performed their small-hole drilling in soundproof rooms to eliminate vibration of very small drills. Air blasts were prohibited from these rooms because they deflect and break the very small drills. Drills were mounted in sealing wax or shellac. Carbon steel has been recommended because it sharpens to a finer edge than does high-speed steel. Pithwood is used to clean drills. In some cases a twist drill is used to rough out holes; hole finishing is performed with half round drills. Most of these approaches, however, were used for drills 0.25 mm diameter or smaller rather than the size used in this study.

Production Economics

Producing high quality miniature holes on a small lot basis is a tedious and time consuming operation. Equations 7, 8, and 9, for example, illustrate the factors which contribute to this cost.

Drilling or Reaming.

$$C = M \frac{D(L + c)}{3.82 f_r v} + \frac{R}{r} + t_L + \frac{t_o}{N_L} + t_i + \frac{L t_d}{T_t} + \frac{LC_p}{T_t} \quad (7)$$

$\uparrow$
 $\frac{\$}{\text{Min}}$

$\uparrow$
 Feeding
Time

$\uparrow$
 Rapid
Traverse
Time

$\uparrow$
 Load
and
Unload
Time

$\uparrow$
 Setup
Time

$\uparrow$
 Cutter
Index
Time

$\uparrow$
 Drill
Replacement
Time

$\uparrow$
 Tool
Tool
Depreciation
Cost

Drilling and Reaming.

$$t_m = \frac{D(L + c)}{3.82 f_r v} + \frac{R}{r} + t_i + \frac{L t_d}{T_t} \quad (8)$$

Equation for Production Rate.

$$P = \frac{60}{\left(\sum t_m + t_L + \frac{t_o}{N_L} \right)} \quad (9)$$

Table 12 defines each symbol used and lists some data applicable to some parts. When the data for drilling only are used, the

Table 12. Symbols for Cost and Production Rate Equations

Symbol	Item	Data for Example	
		Drill Only	Drill Centerdrill Bore, Ream
C	Cost for manufacturing one workpiece; \$/workpiece.	---	---
C_p	Purchase cost of tool or cutter; \$/cutter.	\$4.00	\$12.00
D	Diameter of tool in milling, drilling, reaming, tapping; (in.).	0.025	0.025
e	Extra travel at feedrate (f_r or f_t) including approach, overtravel, and all positioning moves; (in.).	1.00	4.00
f_r	Feed per revolution; (in/rev).	0.0005	0.0005
L	Sum of length of all holes of same diameter in drilling, reaming, tapping; (in.).	0.480	1.500
M	Labor + overhead cost on drilling machine; (\$/min).	\$0.42	\$0.42
N_L	Number of workpieces in lot.	75	75
P	Production rate per 60-minute hour; (workpieces/hr).	---	---
r	Rapid traverse rate; (in./min).	6.0	0
R	Total rapid traverse distance for a tool on one part; (in.).	16.0	64.0
t_d	Time to replace dull cutter in tool changer storage unit; (min).	10	20

Table 12 Continued. Symbols for Cost and Production Rate Equations

Symbol	Item	Data for Example	
		Drill Only	Drill Centerdrill Bore, Ream
t_i	Time to index from one type of cutter to another between operations (automatic or manual); (min).	1.0	4.0
t_L	Time to load and unload workpiece; (min).	1.0	1.0
t_m	Time (average) to complete one operation; (min).	---	---
t_o	Time to set up machine tool for operation; (min).	180	240
T_t	Tool life measured in inches of travel of tool to dull a drill, reamer, tap; (in.).	9.6	5.0
v	Cutting speed; (ft/min).	23.6	23.6

cost elements given in Table 13 result. As noted there, the cheapest cost element in drilling is the cost of the drill. For this reason, and the fact that if drill quality is below requirements the setup costs and tool change costs increase quickly, it is important to assure that drill geometry requirements are rigidly maintained.

Table 13 also indicates that setup time is one of the most expensive factors in precision drilling. With requirements of a 25.4 μm tolerance on location, and tighter tolerances on size, setups must be performed with painstaking accuracy. Each tool change requires another check on size and location. The large cost for rapid travel time is one item that can be reduced by keeping the spindle head closer to the workpiece. This particular example, however, does not include any time to position the spindle over the next hole. In most situations table movement time would be as expensive as rapid travel time.

These cost figures are based on 3600 RPM speed, 8 holes per part, a drill life of 20 parts, the use of a manual jig borer, and a commercial rate of \$25 per hour for labor plus overhead. The use of automatic screw machines for the production of a single hole would be significantly faster. If the hole production process includes centerdrilling, drilling, boring, and reaming, the total cost of operation will be approximately three times the cost shown in Table 13.

Figure 20 provides an estimate of how hole location and size tolerance affect costs per part when drilling flat plates. One significant factor not mentioned thus far is that as tolerances decrease the number of defective parts increases rapidly which inflates the costs quickly. In addition, the need for more frequent in-process gaging increases as does the time required to perform each gaging operation. Different materials and deeper holes would significantly alter these curves. Table 14 presents the apparent most economical production technique based upon the conditions used in this study.

Additional Observations

In this study, three commercial machines were used to evaluate drilling performance. Bendix Kansas City, however, has 12 different types of machines often used for small-hole production. As indicated in Appendix Table D-1, the size capability as well as the operating feeds and speeds vary considerably.

The best drills used in this study can be fed at a constant rate with no apparent adverse side effects. As drill sizes become smaller, however, it is probable that a more sensitive feeding mechanism would be required. One such possibility would combine the characteristics of programmable robots and torque/thrust

Table 13. Calculated Cost per Part for Drill-
Only Data Listed

Item	Cost (Dollars)	Time (Minutes)
Time in Cut	0.13	0.32
Rapid Traverse Time	1.12	2.67
Load/Unload	0.42	1.00
Setup	1.01	2.40
Tool Replacement	0.21	0.50
Drill Cost	0.20	---
Cost per Part	\$2.99	---

sensing controls. A memory device would be attached to the unit. The first hole would be handfed to allow operator judgment to determine speeds, feeds, chip clearing cycle, and other parameters. The memory unit would retain these exact motions, in addition to monitoring drill torque and thrust. These instructions could then be used to drill remaining parts automatically. They could also be punched automatically onto an N/C tape for use on future parts. A feed/speed override would be built into the unit to account for drill wear.

Drilling represents one of more than 40 methods used for producing holes. Electrochemical machining, electrical discharge machining, and micropiercing, for example, appear to have quality as well as economical advantages in some small-hole applications. Combinations of these processes and conventional drilling have also been able to produce high quality, low cost holes. A combination of drilling and shaving, for example, has been used at Bendix Kansas City for several years to produce holes with a 10.16 μm size tolerance. That process has been shown to be a repeatable process on some parts for hole location tolerances as low as 5.08 μm . A better understanding and comparison of all the precision hole production processes would provide both quality and economic advantages. Reference 13 provides a partial listing of articles useful in such a project.

Figure 20. Estimate of Tolerance Influences on Costs

ACCOMPLISHMENTS

The rigidity and strength of these miniature drills have been analyzed empirically and analytically. A computer program has been developed which calculates these properties for twist drills. Drilling forces have been measured. A study of seven commercial drill geometries was performed which indicated that printed circuit board drills and chisel-point drills can produce hole patterns having positional tolerances of 25.4 μm . Size tolerances of 0.625 mm holes can be maintained to $\pm 5.08 \mu\text{m}$. Centerdrilling is not required for some drills to produce precision holes, and boring is also an unnecessary operation. Spindle speed and feed-rate effects were studied as were the effects of chip clearing actions. These studies have provided new insights into the capabilities of small-hole drilling.

FUTURE WORK

This development studied only one basic drill diameter and a nominal depth of 2-1/2 diameters. Although these conditions are representative of approximately 50 percent of Bendix Kansas City requirements, a need also exists for deflection and size data on

Table 14. Technique Apparently Most Economical

Positional Tolerance (μm)	Drilling Technique*			
	Centerdrill, Drill, Ream	Drill, Ream	Centerdrill, Drill	Drill Only
± 2.5				
25	X			
50	X			
75		X		
125		X		
± 7.6				
25	X			
50	X			
75		X		
125		X		
± 12.7				
25	X			
50	X			
75				X
125				X
± 25.4				
25	X			
50				X
75				X
125				X

*Assumes 0.65 mm through hole in 1.825-mm-thick stock having a flat starting surface. These recommendations do not take into account any differences which might occur in deburring times because smaller burrs result from one approach. The use of chisel-point drills requires centerdrilling.

smaller drills and greater depth/diameter ratios. Future studies should explore factors in drilling holes:

1. The techniques required to drill precision miniature holes in stainless steel with depth/diameter ratios of 10 to 20.
2. The techniques and equipment required to produce precision multiple holes, using 0.127- to 0.500-mm diameter drills.

3. Alternate machining processes for producing precision miniature holes.
4. The causes of drill deflection as related to specific drill geometry, machine tool, and dynamic conditions.

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Appendix A

CALCULATION OF APPROXIMATE VARIANCE FOR ANY ARBITRARY FUNCTION

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CALCULATION OF APPROXIMATE VARIANCE FOR ANY ARBITRARY FUNCTION

As discussed elsewhere,^{14,15} any function of n variables $f(x_1, x_2, x_3, \dots, x_n)$ can be expanded into a Taylor series about a particular point such as $(x_1^*, x_2^*, \dots, x_n^*)$. Then the expected value (mean) of the function can be given approximately by

$$E[f(x_1, x_2, \dots, x_n)] \approx f(x_1^*, x_2^*, \dots, x_n^*), \quad (A-1)$$

and the variance of the function is approximately given by

$$\begin{aligned} \sigma_f^2(x_1, x_2, \dots, x_n) &\approx \sigma_{x_1}^2 \left[\left. \frac{\partial f}{\partial x_1} \right|_{x_1^*, x_2^*, \dots, x_n^*} \right]^2 \\ &+ \sigma_{x_n}^2 \left[\left. \frac{\partial f}{\partial x_n} \right|_{x_1^*, x_2^*, \dots, x_n^*} \right]^2. \end{aligned} \quad (A-2)$$

For a radial distribution,

$$r = [x^2 + y^2]^{1/2}, \text{ and} \quad (A-3)$$

$$\begin{aligned} \sigma_r^2 &\approx \sigma_x^2 \left[\left. \frac{1}{2} (2x) (x^2 + y^2)^{1/2} \right|_{\bar{x}, \bar{y}} \right]^2 \\ &+ \sigma_y^2 \left[\left. \frac{1}{2} (2y) (x^2 + y^2)^{1/2} \right|_{\bar{x}, \bar{y}} \right]^2 \\ &\approx \left[\sigma_x^2 \left. \frac{x}{\sqrt{x^2 + y^2}} \right|_{\bar{x}, \bar{y}} \right]^2 + \left[\sigma_y^2 \left. \frac{y}{\sqrt{x^2 + y^2}} \right|_{\bar{x}, \bar{y}} \right]^2 \\ &\approx \sigma_x^2 \left[\frac{\bar{x}}{(\bar{x}^2 + \bar{y}^2)^{1/2}} \right]^2 + \sigma_y^2 \left[\frac{\bar{y}}{(\bar{x}^2 + \bar{y}^2)^{1/2}} \right]^2. \end{aligned}$$

$$\text{Thus, } \sigma_r = \frac{[\bar{x}^2 \sigma_x^2 + \bar{y}^2 \sigma_y^2]^{1/2}}{[\bar{x}^2 + \bar{y}^2]^{1/2}} \quad (\text{A-4})$$

Appendix B

REPEATABILITY OF HOLE LOCATION

Table B-1. Repeatability of Hole Location

Process	Material	σ_x (μm)*	σ_y (μm)*	σ_{rT} (μm)*	F Ratio
1	Brass Stainless Steel			17.132	
2	Brass Stainless Steel	2.687 2.620	5.744 5.220	5.042 4.610	4.6 4.0
3	Brass Stainless Steel	2.320 3.444	3.259 5.018	2.934 4.516	2.0 2.1
4	Brass Stainless Steel	3.047 7.667	3.465 6.741	3.327 7.371	1.3 1.3
5	Brass Stainless Steel	10.253 4.154	10.468 3.276	10.538 3.835	1.0 1.6
6	Brass Stainless Steel	3.623 14.064	3.596 18.274	3.625 16.751	1.0 1.7
7	Brass Stainless Steel	7.451 5.945	6.266 9.267	7.079 8.186	1.4 2.4
8	Brass Stainless Steel	308.864 30.414	234.109 31.824	288.206 31.293	1.7 1.1
9	Brass Stainless Steel	2.478 1.500	3.729 2.179	3.406 1.961	2.3 2.1
10	Brass Stainless Steel	14.093 5.938	7.448 11.077	12.355 9.710	3.6 3.5
11	Brass Stainless Steel	5.283 5.183	4.158 13.494	4.912 11.605	1.6 6.8
12	Brass Stainless Steel	22.505 15.369	10.568 15.408	19.728 15.387	4.5 1.0
13	Brass Stainless Steel	4.928	2.645	4.321	3.5
14	Brass Stainless Steel	7.591 2.565	2.960 2.698	6.604 2.698	6.6 1.1
15	---				

Table B-1 Continued. Repeatability of Hole Location

Process	Material	σ_x (μm)*	σ_y (μm)*	σ_{r_T} (μm)*	F Ratio
16	Brass	2.341	6.022	5.220	6.6
	Stainless Steel	4.901	4.367	4.575	1.3
17	Brass	1.508	2.052	1.867	1.9
	Stainless Steel	54.910	24.223	48.138	5.1
18	Brass	9.705	4.017	8.410	5.8
	Stainless Steel	1.628	4.236	4.094	6.8

*Values of standard deviation in x, y, and r directions.

Appendix C

BASIC STEPS FOR CALCULATING STANDARD
DEVIATIONS AND DIAMETER REQUIRED TO
ACCOMMODATE A SELECTED PERCENTAGE OF
ACTUAL HOLE LOCATIONS

Appendix C

BASIC STEPS FOR CALCULATING STANDARD DEVIATIONS AND DIAMETER REQUIRED TO ACCOMMODATE A SELECTED PERCENTAGE OF ACTUAL HOLE LOCATIONS

I VARIATION OF HOLES FROM DESIRED HOLE LOCATION σ_{FA} (INCLUDES SETUP ERRORS)

- Use raw inspection data.
- Determine x and y position relative to desired position for each hole in each plate.
- Pool all results.
- Solve for σ_x and σ_y .
- If $\sigma_x = \sigma_y$, then σ_r (σ_{rA} in this case) = $\sigma_x = \sigma_y$.
- If $\sigma_x \neq \sigma_y$, use Equation 1 in the main body of this report to find an approximate σ_r (σ_{rA} in this case).
- To find the locational diameter required to accommodate 99 percent of all holes produced, use twice the value calculated by Equation 4.

II VARIATION OF HOLES FROM DESIRED HOLE LOCATION σ_{rT} (AFTER TRANSFORMING DATA TO REMOVE SETUP ERRORS)

- Use transformed least squares data.
- Determine x_1 and y position relative to desired position for each hole in each plate.
- Pool all results.
- Solve for σ_x and σ_y .
- If $\sigma_x = \sigma_y$, then σ_r (σ_{rt} in this case) = $\sigma_x = \sigma_y$.
- If $\sigma_x \neq \sigma_y$, then one must use tables such as Harter's¹⁶ to determine the effective radius that corresponds to a given probability of measurements falling within the

circle described by $A\sigma_r$ where A is a constant.* As an example, if 99 percent of all falls must fall within the radius $3\sigma_r$, and if $\sigma_x = 0.00010577$ and $\sigma_y = 0.00022615$, then from Harter's Table 2,

$$K \approx 2.633, \text{ and since } K\sigma_y = A\sigma_{r_T}, \quad (C-1)$$

$$\sigma_{r_T} \approx \frac{K\sigma_y}{A} = \frac{2.633}{3.00} (0.00022615) = 0.00019848.$$

- If $\sigma_x = \sigma_y$, then twice the value calculated by Equation 4 will provide the diameter required to contain any specified percentage of holes.
- If $\sigma_x \neq \sigma_y$, then one must use Harter's tables and the procedures described above (Equation C-1). The data presented in this report are based on 99-percent probability. If other values of probability are desired, the value of K in Harter's table and A in the above equation will differ from that used in this report.

III VARIATION OF HOLES FROM DESIRED HOLE LOCATION σ_{r_D} (σ_{r_T} OFFSET FROM DESIRED HOLE PATTERN LOCATION)

- Calculate σ_{r_t} as indicated in II.
- Calculate the pooled dimension r_D (Figure 4).
- Use the tables in reference 17 or the approaches described by others¹⁸⁻²² to find the diameter required to contain any specified percentage of holes.

*Note that a least squares fit causes $\bar{x}$ and $\bar{y}$ to go to zero, which negates the usefulness of Equation 1. Techniques other than Harter's are available for certain classes of this problem.

Appendix D

SMALL HOLE DRILLING EQUIPMENT USED
AT BENDIX KANSAS CITY

Table D-1. Small Hole Drilling Equipment Used at Bendix
Kansas City

Number	Equipment	Typical Range of Drill Sizes (in.) (mm)	Typical Capabilities and Limitations*
A	Small Drill Presses	0.025 to 0.375 (0.64 to 9.53)	Hand feed Speeds: 6 spindles/bench
B	Najet Ultra- Sensitive Drill	0.0001 to 0.015 (0.003 to 0.038)	Hand feed 9 speeds: 1300 to 3400 RPM Positioning accuracy: Probably ± 0.00025 (± 0.0064) (All hand movement)
C	Posalux Precision Copy	0.0016 to 0.160 (0.041 to 4.06)	Infinitely variable feed: 0.024 to 12 IPM (0.61 to 305 mm/min) Pecking action available Hole location produced by template
D	Tornetic Tapper	0.010 to 0.250 (0.25 to 6.35)	Feed Variable speed: 0 to 2500 RPM Positioning: Manual Torque control overrides feedrate; gives pecking action.
E	WSI Heads (BKC Gen K 2286) Finishing Operation Only	0.020 to 0.250 (0.51 to 6.35)	Variable feed: 0.4 to 10 IPM (10.2 to 254 mm/min) Fixed speed control- led by gears 1 to 20 spindles per cycle Fixed positioning

Table D-1 Continued. Small Hole Drilling Equipment Used at Bendix Kansas City

Number	Equipment	Typical Range of Drill Sizes (in.) (mm)	Typical Capabilities and Limitations*
F	Manual Jig Borers	0.010 to 0.125 (0.25 to 3.18)	Hand feed only 6 Speeds: 430 to 3600 RPM Positioning accuracy: 80×10^{-6} (2.03 μ m) Single spindle Manual positioning
G	N/C Jig Borers	0.010 to 0.125 (0.25 to 3.18)	Hand or 6 machine feeds: 0.0008 to 0.007 IPR (0.020 to 0.18 mm/R) 8 Speeds: 75 to 2000 RPM Positioning accuracy 80×10^{-6} (2.03 μ m) Single spindle
H	N/C Drills (Burgmaster 25III)	0.030 up (0.76 up)	Infinite feed: 0.1-89.1 IPM (2.5 to 2263.1 mm/min), + override Infinite speed: 60 to 6000 RPM Pecking action available Positioning accuracy: ± 0.0005 (± 0.013 mm) 8 Spindles
I	Levin Lathes	0.003 to 0.125 (0.08 to 3.18)	Hand feed 8 Speeds: 350 to 3000 RPM Positioning accuracy: Probably ± 0.0002 (± 0.005 mm) Single spindle

Table D-1 Continued. Small Hole Drilling Equipment Used at Bendix Kansas City

Number	Equipment	Typical Range of Drill Sizes (in.) (mm)	Typical Capabilities and Limitations*
J	Small Hardinge Lathes	0.020 up (0.51 up)	Infinite feed: 4 to 10 IPM (102 to 254 mm/min) Variable speeds: 125 to 3000 RPM Positioning accuracy: Probably ± 0.0001 (0.003 mm) Single spindle
K	Automatic Screw Machines	0.010 up (0.25 up)	Cam feeds: 0.0001 to 0.020 IPR (0.003 to 0.51 mm/R) Variable speeds: 840 to 8050 RPM Positioning accuracy: 0.0005 concentricity (0.013 mm) Single spindle
L	Small EDM Unit	0.004 to 0.060 (0.10 to 1.52)	Variable feed: Probably 0.0005 to 5 IPM (0.013 to 127 mm/min) Speed: Not applicable Positioning accuracy: Probably ± 0.0002 (± 0.005 mm) Single spindle

*This list represents typical limits, but it should not be used as the sole source for selecting processes or specifying tolerances. Additional special purpose equipment is available for plastic parts and printed circuit boards.

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Miniature components for precision electro-mechanical mechanisms such as switches, timers, and actuators typically require a number of small holes. Because of the precision required, the workpiece materials, and the geometry of the parts, most of these holes must be produced by conventional drilling techniques. The use of such techniques is tedious and often requires considerable trial and error to prevent drill breakage, minimize hole mislocation and variations in hole diameter.

MECHANICAL: Drilling Miniature Holes

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This study of eight commercial drill designs revealed that printed circuit board drills produced better locational and size repeatability than did other drills when centerdrilling was not used. Boring holes 1 mm in diameter, or less, as a general rule did not improve hole location in brass or stainless steel. Hole locations of patterns of 0.66-mm holes can be maintained within 25.4- μ m diametral positional tolerance if setup misalignments can be eliminated. Size tolerances of $\pm 3.8 \mu$ m can be maintained under some conditions when drilling flat plates. While these levels of precision are possible with existing off-the-shelf drills, they may not be practical in many cases.

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