INSPECTION CONSIDERATIONS FOR HOLES
0.040 INCH AND SMALLER

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Micro Holes HOLES 0.040 INCH AND SMALLER

Kansas City Division*

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ABSTRACT

The accurate inspection of hole size and location for holes smaller than 0.040 inch necessitates several considerations beyond those normally encountered for larger holes. The technical aspects are described herein.

INTRODUCTION

Because of their unique size, miniature holes present a major problem just in their manufacture. In some instances, these are produced in hard-to-machine materials. In some places, very precise tolerances with low-precision edge conditions are required. Authorities have indicated that the quantity of these precision holes is increasing rapidly, compared to demand and production years ago. At one time, quantities of a few hundred holes were being requested of vendors capable of producing them. Currently, designers are asked for hundreds of millions of these precision holes.

The manufacture of many precision miniature holes represents a state-of-the-art capability in itself. In many situations, however, some users require only low quantities and appropriate equipment is not available to manufacture them most economically. Similarly, lead times and a variety of other conditions limit the availability of using some of the most appropriate equipment. The manufacture of holes is only one part of the problem, and the ability to inspect holes, invisible to the unaided eye in some cases, is another.

A size example is a conventional mechanical drill or reamer as small as 0.000050 inch. That holes so small can be drilled when the unaided human eye can see a hole no smaller than 0.003 inch demonstrates some of the special requirement difficulties. Although these holes are obviously very small, holes are being produced as small as 0.0000005 inch in diameter (1/2 millionth of an inch). Clearly, a major difference exists in techniques required to measure size of holes 0.060 inch in diameter, 0.003 inch in diameter, 0.000050 inch in diameter and 0.0000005 inch. Special attention is necessary for instruction techniques and consideration for measuring these miniature holes.

Several aspects must be considered in planning hole measurement. These include

- the exact definition of what one expects of the hole;
- an understanding of the basic measurement approaches and their limitations;

- an understanding of equipment used;
- an appreciation of statistics involved;
- an understanding of the problems of people who must perform the measurement.

Definition of Hole Characteristics

One of the most overlooked facets of hole inspection is defining desired hole characteristics. For example, Figures 1 and 2 list some attributes of a hole. Stating the size of these holes often requires more than one characteristic. Measurement of these holes by a variety of processes or approaches produces a similar variety in results. Although some may question the reality of shapes in Figure 1, it is important to recognize that these and other shapes do exist on every hole, particularly those with tolerances in millionths of an inch.

The question to be asked is, "What do I measure?" or, "How do I measure to get the needed information?" The answer depends, of course, upon hole function. Holes used for rotating shafts may require different inspection techniques than those used for fluid flow or other applications. Thus, no absolute answer exists about hole size. The approach to measure holes must be directly related to the use of those holes.

Another consideration is hole location. Figure 3, for example, illustrates two conditions in which roundness must be considered. In the first condition, the location of the shaft put in the hole corresponds to most of the hole contour. In the second case, the bump in the hole will move the shaft significantly. Thus, factors indicated in Figures 1 and 2 directly may influence hole location.

Approaches to Size Measurement

A closer look at some inspection practices on larger parts reveals some of the expected problems in measuring hole size accuracy.

Hole Size Accuracy

For hole measurement, three basic approaches are common:

- Mechanical size wires or gages;
- Optical techniques; and
- Flowrate techniques.

Flowrate techniques are commonly used in industries where some form of fluid flow passes through the hole. A typical example would be holes produced in diesel injection nozzles or carburetor

ROUNDNESS

CAMMING

CONCENTRICITY

ALIGNMENT

STRAIGHTNESS

BARREL SHAPE

HOUR GLASS

BELL MOUTH

TAPER

SQUARENESS

FLATNESS

RELATIVE SIZE

ABSOLUTE SIZE

LOCATION
(RELATIVE TO ROUNDNESS)

LEAN
(RELATIVE TO OTHER PART FEATURES)

Figure 1. Characteristics of Hole Forms (Courtesy Moore Special Tool Co.¹)

Figure 2. Roundness of Two Holes
(Courtesy Moore Special Tool Co.¹)

Figure 3. Effects of Roundness on Part Fit (Courtesy Moore Special Tool Co.¹)

parts. Many of these holes are, at least in part, calibrated by the quantity of fluid that flows through them, or, in some cases, by the magnitude and shape of the projecting stream exiting from the hole (Figure 4). Some users will use a combination of both plug gaging and flowrates or flow pattern observation, to determine the appropriateness of the hole size and configuration.

Although air-gaging is used for holes 0.125 inch in diameter and larger, it is difficult to do on very small holes. One company, however, has developed a means of using air pressure for measuring hole size as small as 0.009 inch (Figure 5).² In this approach, a known size solid plug gage is inserted in the hole to be measured. A regulated flow of air through the part is impeded by this plug, which causes back pressure monitored and calibrated to provide a size dimension.

Figure 6 illustrates the view of a miniature hole under magnification for inspection. Any size hole can be measured this way. Mechanically produced holes only 0.0015 inch in diameter have been measured using optical jig bore measuring machines at 400X magnification. The problem with these approaches is that only a relative indication of actual size is obtained. Any burrs or material at the tops of the hole will influence the readings. Even smooth holes that are not perfectly round or straight will have the same types of approximation to actual hole size.

Optical methods are used widely to inspect holes, but that does not necessarily imply that they are used with the precision indicated by the values shown on output displays.

At this point it is appropriate to look at the use of wire-type gages and the problems associated with them. Conditions such as bell mouth, barrel shape, or hour-glass shapes all will influence the obtainable size. It is necessary to establish exactly an acceptable amount of bell mouth. Figure 7 illustrates one company's definition of the amount of bell mouth allowable on precision miniature holes.

Consider three conditions of miniature blind holes or counterbored miniature holes. Figure 8 illustrates the situation in which a small burr exists at the entrance of the hole. Even with the use of magnification such as 35X magnification, burrs only 0.0001 inch high are often not seen on holes 0.020 inch in diameter. In many cases, because of the deburring techniques or other manufacturing processes used, these burrs will be extremely small and uniform. From a look at the surfaces or tipping that part at an angle, the burrs may be so uniform that it appears they have been removed. This is not necessarily the case. To determine whether burrs exist in such conditions, it is necessary to physically probe the hole with a small tool. On many parts, such a small burr does

Figure 4. Accepting Hole Quality Based on Fluid Stream Characteristics

not represent a problem. However, on holes with tolerances of ± 0.0002 inch, it is imperative that all such projections be removed.

Figure 9 illustrates a small diameter and shallow counterbore. The radius on the end of the size wire is large enough to impede getting an accurate measurement of the counterbore size.

Most size wires have been recalibrated in the center of the wire and somewhere near the ends. In most through-hole applications, this is acceptable. For a shallow counterbore such as this, however, a nearly sharp-edged size wire is necessary for measurements. Apparently, many size wires provided commercially have a 0.005 inch radius or larger on the ends. After use, of course, this radius will increase.

Size wires can change rapidly, particularly at their ends, when inserted into holes. Changes will make their use on blind holes or shallow counterbores similarly inaccurate (Figure 10). Some precision users of these wires will trace the profile to the very ends to verify that wear is not present in measurable amounts.

"How large a gage can I put into a hole?" A frequent assumption is that putting in a gage larger than the actual diameter of the hole is impossible. Some users, however, indicate that flushing the gage and hole surface with alcohol enables a wire 0.0001 inch larger than the hole to enter the hole. The implication here is

Figure 5. Using Back Pressure on Air Gage to Measure Hole Size (Courtesy American Machinist)

that other cleaning solutions will not allow this to happen, and there is no good explanation as to why this happens. A number of factors may be involved. Though several people have reported this phenomenon, the question "How does one know what the hole size is accurately before the gage is inserted?" must be considered.

Another assumption is that inserting a gage into a hole will not affect hole size. However, a gage can easily affect hole size of holes having tolerances of ± 0.0002 inch on holes 0.020 inch in diameter or smaller. The problem confronting inspection is, "How can one verify that the hole does not exceed a certain dimension when the gage may cause it to exceed those dimensions?" For example, for a hole within 0.0001 inch of the high limit, what gage should be called out to inspect that hole?

Figure 6. Optical View of
Miniature Hole

One company established a 0.0001-inch limit under high limits for the maximum allowable gage inserted into a hole. In the case of smaller holes, the gage may enlarge them to gage size. The resulting hole, however, still will be 0.0001 inch smaller in diameter than the allowable drawing dimensions.

"What happens when this 'no-go' gage goes?" No easy answer exists, except estimation about whether the next-larger 0.0001 inch-size would fit.

It is possible to use gages manufactured in increments of 50 millionths of an inch rather than 0.0001 inch. These become very costly, however, as the size of the gages decreases. Table 1, for example, illustrates quoted costs for some miniature size wires. Some of these wires cost almost \$90 each in 1979. The advantage of using undersize gages for checking size is that this technique is a form of narrow limit gaging quality, perhaps to a higher level than required, but it prevents damage to surface finishes as well as to hole size.

Another concern, temperature effects in gaging, is generally not significant in itself for measuring miniature features. For example, to measure a 0.020 inch diameter hole with a size wire, an assumed product thermal expansion coefficient of 0.000006 inch an inch for each Farenheit degree would permit the hole to grow only 0.1 microinch for each degree F. Thus, even a temperature change of 100°F will permit only a growth change of 0.000010 inch. For the degree of accuracy required on most parts, this is not significant, especially because many temperature changes would be only about 10°F, affecting a part only one millionth of an inch.

Figure 7. One Company's Written Standard for Allowable Bell Mouth

Although optical means or a fixed size plug member are used to gage holes, it is possible to utilize an expanding split probe to measure size (Figure 11). The smallest standard size available is 0.0185 inch. Basic design of this device is suited to holes with lengths at least equal to diameter, because as lengths become shorter this approach loses accuracy. The probe is graduated in 0.0001 inch increments.

By using a ball indicator probe, researchers have developed equipment that will contact both sides of a hole and automatically calculate hole diameter.^{3,4,5} This technique has been used on holes as small as 0.020 inch to an accuracy of ± 0.00002 inch, and, of course, assumes that two simple point contacts satisfactorily define hole size. Russian researchers, using a similar approach but adding optical evaluation of point of contact, state that a measuring accuracy of 0.000063 inch can be achieved for holes 0.040 inch and larger.⁶

SMALL BURR (0.0001 INCH HIGH) NOT VISIBLE WITH
MICROSCOPE AT 30X. HOLE MUST BE PROBED TO FIND THE BURR.

Figure 8. Small Burr at Hole Entrance

Absolutely imperative for accuracy in any precision work is the cleanliness of inspected parts, gages, and features. Without attention to cleanliness, it is impossible to obtain accurate measurements.

Roundness and other aberrations in Figure 1 affect the working size of many holes. As in Figure 12, all of the shafts and holes illustrated have a measured size of 1.000 inch across any diameter, but only the truly round parts have an effective size of 1.000 inch.

The effective size of a shaft or other outside diameter is the size of the smallest actually round hole that the part will go into.

Figure 9. Radius on End of Size Wire Gage Masks True Counterbore Size

Gage Accuracy

Gage accuracy is in itself a source of potential measurement error. Federal specification for size wires or plug gage members only cover sizes down to 0.031 inch. These standards (MIL-STD110A and 111A) do not indicate the class of accuracy often required.

NOTE: ARE SIZE WIRES CALIBRATED ON ENDS OR ONLY IN THE CENTER?

Figure 10. Wear on Size Wire Ends Masks the Actual Hole Size

The Federal standard H-28 for screw threads, however, includes a table providing recommended gage accuracies at several levels for various size wires (reference Table 6.14 in MIL-HDBK-28). Table 2 illustrates the standard gage maker's tolerance chart of accuracy classes for these miniature wires. Wires as small as 0.001 inch in diameter with accuracies of 5 millionths of an inch are available. Tables 3 and 4 indicate values used by one company for precision miniature size wires.

As indicated in Table 3, for product tolerances of 0.0002 inch total the same company recommends the use of XXX gage tolerances. As tolerances increase, the allowable gage tolerance similarly

Table 1. Tungsten Carbide Wire-Type Plug Gages

Range (Inch)		Class	Tolerance (In.)	Price*
Above	To			
.010	.016	XXX	.00001	87.75
		XX	.0002	58.50
		X	.00004	44.55
		Y	.00007	40.20
		Z	.00010	37.60
.016	.030	XXX	.0001	61.70
		XX	.00002	40.90
		X	.00004	36.90
		Y	.00007	34.25
		Z	.00010	32.95
.030	.075	XXX	.00001	45.75
		XX	.00002	30.45
		X	.00004	26.60
		Y	.00007	26.15
		Z	.00010	23.80

*1979 price in quantities of one.

increases. In using these tables it is important to note that the tolerances quoted in those classes (Tables 2 and 3) imply + tolerance - 0. As an example, from Table 2 a class XXX for 0.010 inch diameter wires implies a gagemaker's tolerance or accuracy of the gage of +0.00001 inch - 0. After these wires are used, however, accurate recalibration is a concern. No easy answer exists to this concern, but one company using laser measurement techniques recertifies these gages to a $\pm$ tolerance, as indicated in Table 4.

Recent use of these miniature precision size wires has indicated that, although readings can be taken along the entire length of the wire, many of these wires are not round nor are they straight. This deviance can produce erroneous size information for miniature holes, particularly long holes.

Accuracy of Hole Location

Figure 13 illustrates the use of an indicating probe to sweep a hole to define its location. This is possible for most large

Table 2. Standard Gagemakers Tolerance Chart

Range (Inch)		CLASS*					
Above	To and Including	XXXX	XXX	XX	X	Y	Z
.0009	.010	.000005	.00001	.00002	.00004	.00007	.00010
.010	.029	.000005	.00001	.00002	.00004	.00007	.00010
.029	.825	.000005	.00001	.00002	.00004	.00007	.00010
.825	1.510	.000008	.000015	.00003	.00006	.00009	.00012
1.510	2.510	.00001	.00002	.00004	.00008	.00012	.00016
2.510	4.510	.000013	.000025	.00005	.00010	.00015	.00020
4.510	6.510	.000017	.000033	.00006	.00013	.00019	.00025
6.510	9.010	.00002	.00004	.00008	.00016	.00024	.00032
9.010	12.260	.000025	.00005	.00010	.00020	.00030	.00040

*Tolerances are in inches.

Table 3. Standard Plug and Ring Gage Classes for Product Tolerances

Product Tolerances (Inch)	Size Range* (Inch)			
	0.0020 to 0.8250	0.8251 to 1.5100	1.5101 to 2.5100	2.5101 to 4.5100
.0002	XXX			
.0003	XXX			
.0004	XX			
.0005	XX	XX		
.0006	XX	XX		
.0007	X	XX	xx	
.0008	X	XX	XX	
.0009	X	XX	XX	XX
.0010	X	X	XX	XX
.0012	Y	X	XX	XX
.0014	Y	X	X	XX
.0016	Y	Y	X	XX
.0018	Y	Y	X	X
.0020	Y	Y	Y	X
.0022	Y	Y	Y	X
.0024	Y	Y	Y	X
.0026	Y	Y	Y	Y
Larger Tolerances	Y	Y	Y	Y

*Specify class XXX when gaging a shallow blind hold of 0.05 inch depth.

holes, but for very miniature holes the probe is neither practical nor often remotely feasible.

Hole location can be measured optically; by inserting a pin within the hole; and, in some cases, electronically (for example, using wall thickness of tube).

Figure 11. Expanding Probe-Style Hole Size Measuring Device

DIMENSIONS IN INCHES.

Figure 12. Actual Size Versus Effective Size

Table 4. One Company's Gage
Practice for 0.001 to
0.825 Inch Diameter Gages

Class	Gage Status	
	New	Recertified
XXX	+.000010 -.0	±.000010
XX	+.000020 -.0	±.000020
X	+.000040 -0	±.000040
Y	+.000070 -0	±.000070

*Values are in inches.

For most parts, measuring such holes electronically is not possible because of part geometry. Although probes as small as 0.010 inch have been used to indicate the centerline of small holes, this is the exception. As noted elsewhere¹, back-relieving the probe tip gains even more clearance in miniature holes (Figure 14). It is also possible to provide bottom relief on these miniature probe tips to accommodate thin parts (Figure 15).

One machine manufacturer notes that the location of holes as small as 0.020 inch in diameter can be found by indicating a small gage pin like that in Figure 16. This technique may be successful for thick parts, but for thin parts or very small holes it cannot be used. The advantage of indicating a pin rather than hole walls is that a larger diameter probe can be used, which adds to accuracy.

Dimensioning System

No discussion of accuracy in location would be complete without some consideration of bilateral dimensioning versus the "true position" dimensioning system (Figures 17 and 18). The true position dimensioning system provides a consistent definition for measuring or inspecting feature locations. Because it relies on defining three datum surfaces on which the part must rest and how a hole is located relative to the datum surfaces make the system mandatory for accuracy in many applications. The use of true

Figure 13. Using Indicator Probe to Determine Hole Location

position dimensioning adds inherently to the expected accuracy or repeatability in measurement results. A detailed discussion is beyond the scope of this paper, however, the reader is encouraged to pursue the indicated references.^{7,8,9,10}

Burrs

Clearly, a burr on the hole entrance easily can influence apparent hole location. Although some small burrs are relatively uniform in size, trying to maintain locational tolerances in the 0.0001 inch range is very difficult if burr size consistency must be depended on. For accurate hole location measurements, burrs must be removed totally.

Figure 14. Miniature Probe with Back Relief
(Courtesy Moore Special Tool Co.¹)

Figure 15. Bottom-Relieved Probe Tip
(Courtesy Moore Special Tool Co.¹)

Roundness

The effect of roundness on apparent hole location was demonstrated in Figures 1, 2, and 3. An indicator traversing the hole location might provide misleading results on the actual performance of the mating part.

Tapered Probes

On larger holes it is frequently convenient to use a tapered probe on an electronic coordinate measuring machine to find hole location. On holes smaller than 0.020 inch, for example, tapered probes can damage hole entrance, the hole walls themselves, and, if burrs are present, provide misleading results (Figure 19). Consequently, tapered probes are not used frequently for measuring location of these small holes.

Distortion

Although cleanliness affects measurement, one of the greatest causes for error in hole location measurement is either from part distortion or clamping distortion. Some parts will distort

Figure 16. Indicating a Small Pin

because of thermal effects gradually relaxing in the workpieces. For example, in close tolerance measurements, many workpieces may change size or configuration overnight. Other parts because of their very nature (for example, leaf spring-type parts) will distort from pressures of inspecting devices.

Clamping distortion probably remains one of the greatest causes of error for location on precision parts. Distortion can be acute on miniature parts if these parts are not absolutely flat, or if the same clamping approach is not used at each stage in manufacture and inspection.

Equipment Considerations

Regardless of the type of machine used to measure hole locations, several considerations can verify measurement validity.

One of the first steps is to analyze the quoted accuracy of repeatability of the measuring equipment. Frequently, the accuracy of the machine is something less than that actually listed in literature. Similarly, getting better than quoted accuracy from most machines cannot be expected.

Figure 17. Bilateral Dimensioning

Figure 19. Error Caused by Burrs

After purchaser acceptance, doing internal analysis of the accuracy and repeatability of the measuring machine is common. Too often, however, purchasers rely upon this initial machine performance as an indication of actual machine accuracy. Many factors influence the accuracy of a large machine. In some instances, electronics will influence the results; in others, temperature and humidity.

A machine sooner or later will exhibit some wear, so it is necessary to institute an analysis of machine repeatability on some periodic basis. However, all too frequently, an analysis is conducted only after a problem has been identified.

Statistical Influences

One statistical influence is whether to sample inspect or inspect 100 percent. A subject discussed widely in other sources, it will not be discussed here.

For tolerances of ± 0.0002 inch, the standard deviation of size measurements should be less than, or equal to, 0.0001 inch to guarantee size repeatability. Note that this is obtained by dividing the total tolerance range by a factor of four.

$$\sigma_{95 \text{ percent}} = \frac{\text{total tolerance}}{4}$$

The factor 4 is derived from $\pm 2\sigma$, representing a 95 percent probability level. Thus, under reasonable conditions, 95 percent of all measurements would fall within a size span of ± 0.0002 inch diameter if the standard deviation is less than, or equal to, 0.0001 inch.

Most engineers are not satisfied unless the variation in size measurements is at least less than, or equal to, 80 percent of the tolerance range. In this case, the standard deviation of size measurement must be less than or equal to 0.000080 inch.

When we look at repeatability from a mathematical standpoint, we see that it is composed of at least the following two items:

$$\sigma_{\text{OBS}} = \left[\sigma_{\text{process}}^2 + \sigma_{\text{measurement}}^2 \right]^{1/2}$$

If the standard deviation of the hole-producing process were equal to 0.000050 , and the standard deviation of measurement were also 0.000050 , by this equation the observed standard deviation of the hole size would be 0.00007 inch. This very closely approximates the maximum allowable standard deviation discussed.

The implication is that desirable repeatability of the hole-producing process (here defined as standard deviation) be at least as good as 50 millionths of an inch. Similarly, repeatability of measurements should be at least within 50 millionths of an inch to assure that 95 percent of the features inspection would fall within the allowable tolerance range.

It is doubtful that some processes could produce repeatability of hole size within this range, particularly if initial hole production was careless. Similarly, because of each of the previous factors, controlling measurement repeatability within 50 millionths of an inch is in many cases, unlikely.

If size wires are crooked, not round, used incorrectly, and the right gage tolerance is not used, guaranteeing a repeatability of this magnitude is also unlikely. A study of one of the most widely known optical inspection machines indicated a standard deviation of 0.000060 inch after three or four years of use.

Studies of several well-known inspection machines at the author's plant indicated that after several years use, the $\pm 2 \sigma$ levels of repeatability were typically ± 0.0001 inch, and some were as high as ± 0.00048 inch.

Studies of the repeatability of several large optical comparators indicated that dial readings were not accurate and measurements of size on these machines should not be depended upon, unless part tolerances were at least ± 0.005 inch. The recent advent of digital readouts and better machine design have lessened this limitation.

Add an additional term to Equation 2.

$$\sigma_{OBS} = \left[\sigma_{process}^2 + \sigma_{measurement}^2 + 2r_c \sigma_{process} \sigma_{measurement} \right]^{1/2}$$

This term accounts for the correlation coefficient. Although typically no correlation exists among machining processes, and inspection. Occasionally, such correlation does occur. This then affects the observed standard deviation.

Accuracy Versus Repeatability

As most machine tool builders note on their equipment specifications, accuracy and repeatability each are different attributes. Estimates of repeatability alone are not sufficient (Figure 20). It is essential to know that mean hole location results are also correct. Most machine tools and instruments have a bias that increases with use.

When measuring size, the same mean and repeatability concept described for locations applies. Note that all identification of size of miniature size wires is external to the size wire. This allows misidentification of these wires.

Figure 20. Repeatability Versus Accuracy

CONCLUSION

Few studies appear to have been made on the measurement problems of miniature features. People have difficulty seeing miniature

parts and handling them. Even with adequate tools and larger features, studies have shown that more than 60 percent of parts inspected by hand-held instruments did not meet the expected level of accuracy.

Miniaturization brings with it some unique inspection problems, and as noted by Juran,¹²

"It is common experience to find in a plant where accuracy is not properly organized that 30-50 percent of the measuring equipment used is not giving true answers."

Likewise, in the inspection of miniature parts similar inaccuracies exist.

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