PRACTICAL CONSIDERATIONS IN MEASURING WIREDRAWING DIE DIAMETERS

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Practical Considerations in Measuring Wiredrawing Die Diameters

Dr. Deming, the person most often associated with statistical process control, once observed that if you measure something once, you know what size it is; but if you measure it again, you no longer know its size. What Dr. Deming was referring to is the fact that no measurement is exact and thus measurements do not exactly repeat. In other words, the inch that you measure is not the same as the inch that I measure and is not even the same as the inch you measure tomorrow. In order to understand why measurements are not exact and what we can do to make measurements better, we must first look at some basic definitions.

Definitions

There are three terms which are widely used and widely misused in regard to measuring equipment. They are:

1) Resolution,
2) Precision,
3) Accuracy.

Resolution

Resolution is simply the smallest number that can be produced by the measuring equipment. In other words, the number of graduations per inch or meter (or whatever units are being used). In the case of digital equipment the definition is easy since the resolution is simply the smallest numerical increment shown on the display. In analog equipment, a dial indicator with a needle and a continuous scale, for instance, the definition is a little less straightforward since we are allowed to interpolate between marks so that the actual resolution can be better than the value of each division. Unfortunately, resolution by itself doesn't mean much. For example, let us imagine that we are able to put one million marks per inch on a pocket ruler. Would this mean that we could measure to within one millionth of an inch? Not likely. And yet, we could legitimately claim a resolution of one millionth of an inch. So, you can see that while good resolution is a necessary characteristic, it is not sufficient.

Precision

Precision is the relative ability to get the same measurement reading time after time. Using our imaginary pocket ruler and a microscope, imagine taking many measurements of the same object and getting the same readings within plus or minus two marks or plus or minus two millionths of an inch. Now we can say that our precision is plus or minus two millionths of an inch. But are we really measuring within two millionths of an inch? Not necessarily. At this point, we are not sure that the marks are in the right place. But at least with precision we can tell how close the inch you measure now is to the inch you measured yesterday or will measure tomorrow. You just cannot tell how close the measurement you make is to the measurement that I am making. Like resolution, good precision is necessary but it is still not sufficient.

Accuracy

Accuracy is the ability to make a measurement that agrees with a known standard. In our example of the mythical pocket ruler, if the marks were as much as 100 millionths of an inch from their true positions, then our actual accuracy would be the sum of the reading error plus the error in the location of the marks or plus or minus 102 millionths of an inch. This is certainly a long way from either the resolution or precision that we claimed earlier.

Fort Wayne Wire Die, Inc.

With accuracy, we have finally achieved what we were after. With accuracy, we know how close the inch that each of us measures is to both a known standard and to each other.

The problem is that today's electronics make getting small numbers easy but have done little to make those numbers meaningful. Many advertisements put the resolution in very large letters and say nothing about accuracy. The writers know full well that many readers of the advertisements do not know the definitions of the above terms and will therefore believe the measuring instrument to be better than it is. Even worse is the fact that most people believe an electronically generated number to be correct without question when, in reality, electronic measuring equipment has all the same chances for error that mechanical devices do plus the electronics introduce additional possibilities for error.

Common sources of errors in measuring equipment

Calibration. One can legitimately ask how we, as users of measuring equipment, can take a piece of equipment with good resolution and make it have good precision. The answer is not much. Precision has to be built in at the factory. We can, however, take a piece of equipment with good precision and make it accurate by the act of calibration. But calibration is the most fundamental source of error in all measurement equipment. For instance, there is a polished metal bar in Washington that serves as the primary standard for length. It is not perfect in its geometry, so that even perfect measuring equipment will not get perfect readings. That standard, of course, is not for everyday use so standards are made to agree with it. Those standards are used to make other standards, etc. Since nothing in this world is perfect, there is a loss of accuracy at each step. To help reduce this, we now use the wavelength of a certain type of light for our length standard, but again, this standard is usually many generations away from what we get to use.

Analog to digital conversion

The second fundamental error is due to the fact that we live in an analog world. When we write down a measurement, we are using a digital representation of the real thing and it doesn't make any difference whether we do the digital conversion or have electronics do it for us—the reading is still not exact. For example, let us suppose that we have a digital watch that shows only hours. We look at the watch and see that it reads 9 am. A while later we look and see that it reads 10 am. Based on this information we say that one hour has passed, but did it? The first reading could have been 9:00:00 and the second one 10:59:59 so that in fact almost two hours passed. Similarly, the first reading could have been 9:59:59 and the second one 10:00:00 so that perhaps less than a second passed. In other words, all digital readings can be off by plus or minus one count due entirely to the analog to digital conversion process. And some older technology converters have even larger errors. Please note that this type of error cannot be calibrated out. In fact, since it can occur during a calibration measurement as well as during the part measurement, its effect can be doubled under a "worst case" situation.

Linearity and offset

When a measuring instrument exactly agrees with a standard or has a uniform error, it is said to be linear. Fig. 1 is a graph showing the relationship between readings and actual size for imaginary measuring instruments. Line A would be a perfect instrument since its readings exactly agree with the actual size. Line B would be for an instrument which has a uniformly increasing error. It is still linear, however, and could be corrected by changing its scale factor. Line C would be for an instrument which has a constant error. It is also linear and could be corrected by re-zeroing. Unfortunately, the most common situation in electronic instruments is represented by Line D which is not linear and usually not fully correctable. To minimize the errors due to this non-linearity, two calibration points are used. One is usually at zero since it is the easiest. The second one can vary according to the shape of the nonlinearity curve. In the most common case, the curve is close to an arc so the second point is mathematically shown to be best located at 71% of full scale. This is , of course, important to know when doing field recalibrations. Also, the total non-linearity is important to know when selecting a measuring instrument and any reputable manufacturer will list it on the spec sheet and will usually express it as a percent of full scale.

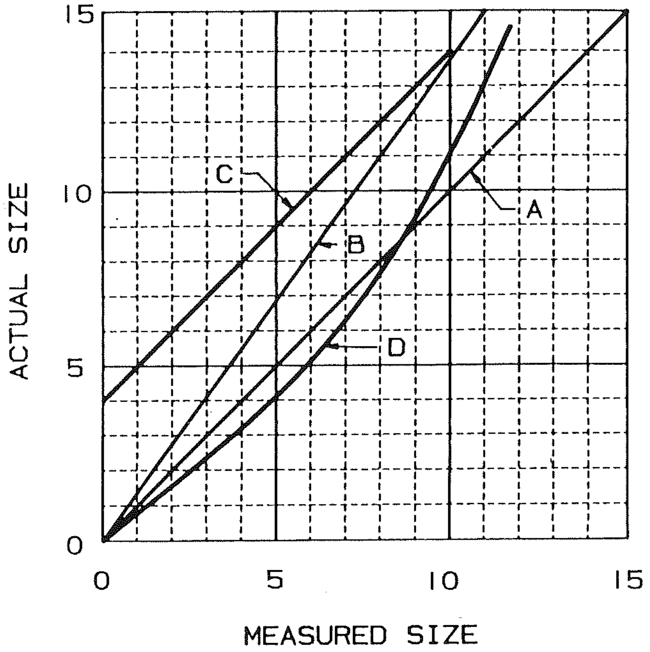


Fig. 1. Effects of nonlinearity and offset.

Drift

The most annoying cause of error is known as drift and is simply the fact that instruments do not stay in calibration. We all realize that things change size with temperature and that things wear, so changes in calibration due to these factors do not surprise us. However, electronic devices have a further drift with time due to the physical way certain electronic materials work. There is nothing that can be done about this problem except to be sure that recalibration is done on a timely basis. Again, manufacturers' literature should list drifts with both time and temperature. These specifications vary in their form and are sometimes expressed as counts, percent of reading, or percent of full scale. These drift errors are added to other errors to determine if the total accuracy is adequate. Also, the drift errors should be looked at carefully to see if the instrument can be used in its environment or with a reasonable amount of recalibration. For instance, a machine located in a draft should not have a large thermal drift. And, similarly, an instrument that drifts rapidly, but has not been recalibrated recently, is highly suspect.

Effect of the instrument on the part being measured

A major consideration in measuring processes has to be the effect of the measuring instrument on the item being measured. For instance, if we were to use a candy thermometer to measure the temperature of a thimbleful of coffee, the thermometer would draw a large amount of the heat from the sample so that the reading would be far from the temperature that the coffee was originally. Or suppose we try to measure a marshmallow with a micrometer as shown in Fig. 2 and tightened the thimble with too much force. All materials distort to some degree when put under pressure so length measurements have to be done under a uniform pressure and calibrated to compensate for the distortion.

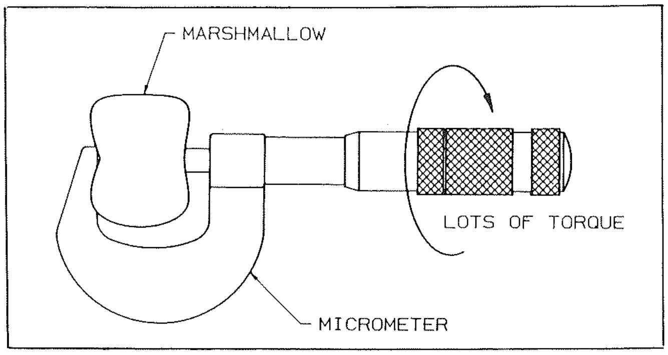


Fig. 2. Effect of measuring instrument on the part to be measured.

Cosine error

The last common source of error to be discussed is related to length type of measurements and is called the cosine error. Fig. 3 illustrates the problem. What we want to measure is dimension A which is the dimension straight across the part. But we may be measuring at an angle as shown as dimension B, which is obviously longer. Since A * Cosine(C), the error is small at small angles but it still exists, must be added to other error, and should be minimized. As an example: A .010 in. wire measured at a 5 degree angle would have a measurement error of 38 millionths of an inch.

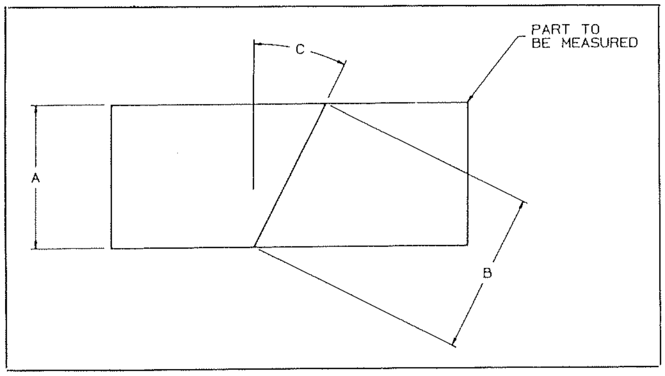


Fig. 3. Cosine error.

Problems unique to measuring the diameter of a wiredrawing die

Whenever the shape of a physical object is changed, two types of deformation can take place: elastic, which is not permanent; and plastic, which is permanent. Often both types of deformation can occur in a single operation. This can be demonstrated by bending a piece of sheet metal. When the piece of metal is released, it will unbend slightly. This is called "springback." The same thing can happen when wire is drawn. The wire can actually be larger than the hole in the die. On the other hand, under certain conditions, the tension on the wire can make it smaller than the hole. In other words, it is highly unlikely that the wire will be the same size as the hole through which it was drawn. This is why we measure the wire instead of the hole in the die when tolerances are critical.

Unfortunately, while this technique eliminates one problem, it creates others. For instance, variations in the feed wire will make a difference in the diameter of the drawn wire. The two most important characteristics are wire size and hardness. These will affect both springback and drawing force and thus final size.

Along with the feed wire, the technique used to draw the wire through the die being tested has a very large effect on the measured wire size. Important factors include the speed of the pull, how straight the wire is pulled through the die, whether or not a lubricant is used, and how much back tension is used on the feed wire.

We must also remember that it is very difficult to maintain uniform conditions and thus wire size in the drawing machine day after day. It is further unrealistic to expect lab results of wire size to exactly duplicate final factory wire size. Most users are therefore happy to make a correlation between test sizes and final product size.

More than anything else, the above should point out the impossibility of tightening wire die tolerances ad infinitum. The wire die tolerances are limited most severely by the ability of today's measurement technology and not by the manufacturing processes themselves. Here is something which might help you visualize the situation. In a diamond, depending on the direction across the crystal, there are at most 164 carbon atoms in a millionth of an inch. So, in order to change the size of a diamond wiredrawing die by a millionth of an inch, you have to remove a layer around the inside of the hole which is a maximum of 82 atoms thick and then be able to measure that you have actually done it!

Popular contact measuring methods

The following analysis of measuring equipment is based on experience. Measuring capabilities are the result of statistical analysis and represent a three sigma limit under ideal conditions. Possible errors due to such things as drift, poor sample preparation, and inaccurate calibration are not included in these figures.

Hand-held micrometers

Contact micrometers of various types are familiar to all of us. Most fundamental is the hand-held micrometer. At best, it is accurate to 0.0002 in. The new electronic hand-held micrometers with digital readouts are really no better even though their resolution is better. The main advantage with the digital readout is that reading errors are vastly reduced and this alone usually makes them worth the extra money. Hand-held micrometers are used when you need a small, portable, easy-to-use device and do not need highly accurate measurements. Just because they do not have the ultimate accuracy, however, does not mean that they can be mistreated. They also need to be serviced on a regular basis to remove the effects of wear and dirt.

Mechanical comparators

Next we should consider the mechanical comparator or "dial indicator". This device simply provides a magnification of mechanical movement usually through a gear rack and pinion. Although a resolution of a few millionths of an inch is obtained with some of them, an actual accuracy of about 15 millionths of an inch is the best we have found. In order to use these instruments successfully, a few rules should be observed. First, through either a weight or a spring mechanism, a uniform pressure against the sample must be produced. Secondly, cleanliness of the instrument and the sample is essential. Third, wear is a factor in any mechanical device so a regular maintenance schedule is required. Fourth, parallax has to be avoided by either a mirrored scale or a sighting device. Finally, good temperature control is needed. The comparators have the advantages of good long-term stability, ease of use and are easily repaired. As with any contact measuring device, the sample is predictably held which all but eliminates the effect of cosine errors. Also readings have no detectable time lag as with some electronic devices which must wait for an analog to digital conversion to take place. And, a needle is often quicker to read when you do not need an exact value but rather just want to know if the reading is within an acceptable range. Disadvantages include wear and the chance of reading errors.

Electronic comparators

Often, mechanical comparators are replaced by LVDTs (Linear Variable Displacement Transformers). These devices work on a magnetic coupling principle where the electrical output depends on where a metallic rod is positioned inside two coils. The output can be displayed with a digital readout or by a needle on a scale. Resolution can be very good, but our tests indicate that the actual best accuracy is still about 15 millionths of an inch as it was with the mechanical comparators. Most advantages and disadvantages are the same also except that there are no mechanical parts to wear out and the readouts can be made more convenient to use. One caution is to be sure to use these instruments in an area which does not contain any strong magnetic fields such as near a large motor or transformer. Extra power line filtering may also be needed if there is the possibility of power surges in your power source. The main drawbacks with this technology are a relatively high drift with both time and temperature and often poor linearity. In fact, the main difference between the cheap units and the expensive ones is how well drift and linearity are controlled.

Glass scale comparators

A final type of contact measuring technology we will discuss is based on an engraved glass scale. The general principle is shown in Fig. 4. One line on a scale would be hard to read, so the scale is set up like a picket fence. As the moving picket fence passes the fixed one, the light is alternatively stopped or let through to a sensor. One advantage of this over a reading a single mark is that an error in the position of a single line has little effect on the overall accuracy. In a practical device, another fixed picket fence and sensor is positioned so that its output is 90 degrees out of phase with first one. This gives four times the resolution and provides a way to tell which direction the scale is moving. Often a third sensor is added to sense the drift due to thermal expansion of the mechanical parts. The output is a sine wave which can be interpolated to yield better resolution than the number of lines per inch that have been engraved on the scale itself. The best resolution we have found with this technology is 2 millionths of an inch with an actual accuracy of about 6 millionths of an inch. The advantages of this technology is that it does not need to be calibrated since that is done by the manufacturer. There is no appreciable drift with time and the drift with temperature is uniform and predictable since it only affects the size of the mechanical parts. Also, errors which are present at any spot only exist there and are not cumulative. About the only real disadvantage is cost when purchasing the very high accuracy models. You should observe the cautions about strong magnetic fields and power surges as noted above.

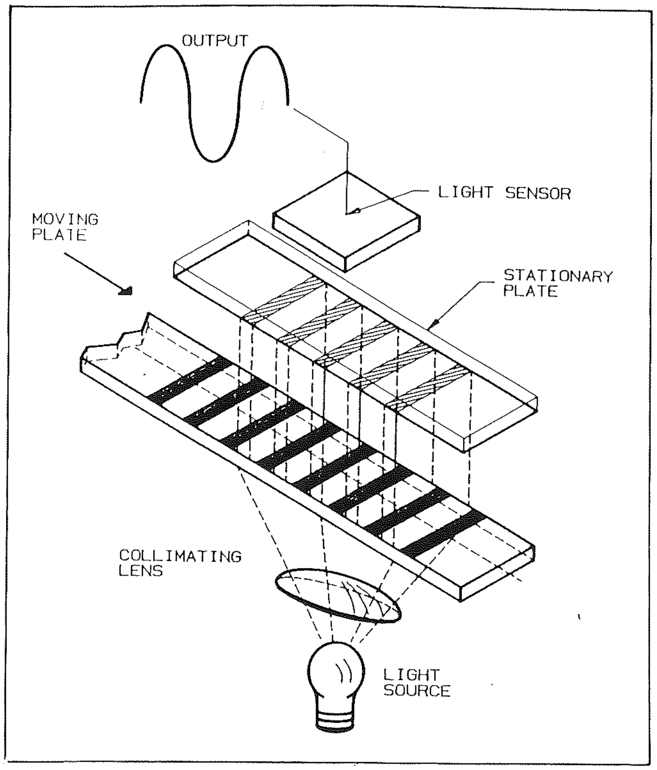


Fig. 4. Glass scale encoder.

There are several other interesting measuring technologies such as laser interferometry, but these are not practical for most of us due to very high cost and the fact that the variability in our wire samples precludes taking advantage of the very high accuracies obtainable.

Popular non-contact measuring methods

Laser optical scanning micrometers. At first glance, optical scanning methods seem to be advantageous. After all, no contact is made with the part so there is no mechanical distortion. Unfortunately, there are several shortcomings which can more than cancel out this advantage. These shortcomings include calibration problems, instability, the wavelength of light, and poor fixturing.

First, let us look at Fig. 5 to see how these devices work. You might have assumed that a continuous sheet of light was used to measure the part. But actually, a small diameter beam of light is swept across the part by a polygonal mirror after being corrected by a lens. A lens on the other end projects the light on a detector. The detector is connected to electronics, which converts the time of light or dark during the sweep into a dimensional reading.

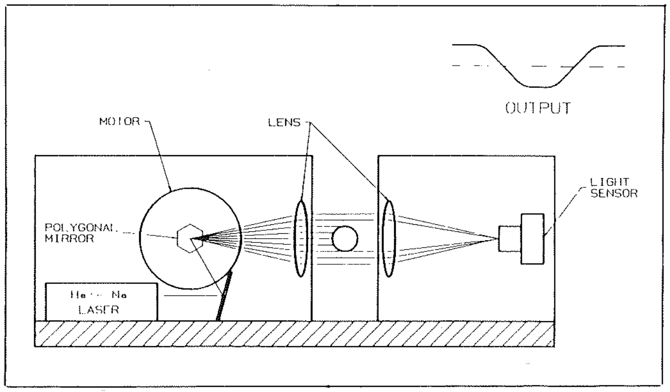


Fig. 5. Laser optical scanning micrometer.

Calibration

There is no way to make a scanned reading directly traceable to the National Bureau of Standards by itself. It is always necessary to calibrate a scanning unit for the conditions for which it is used. The scanning beam has some finite size. Thus, where does a shadow (as detected by a photocell) start and stop? In other words, when is sunup? When the sun first starts to appear? When it is fully visible? Looking at the output curve shown in Fig. 5 you can see that there is not a sharp cutoff and so a level on the curve, shown by the dashed line, has to be selected. And so the calibration, among other things, makes this determination. The problem is that any dirt or smoke will throw off the calibration. This is just like the fact that photoelectrically controlled street lights come on earlier on a cloudy day than on a clear one. A chain smoker operating an optical scan type of measuring system will throw the calibration off in a hurry as will any process smoke, oil vapor, and even heat distortion. Also, you have to remember that any oil film on the sample or calibrating pin will be measured.

Instability

The way a beam is made to scan contributes not only to calibration problems but to instability. Beams are usually made to scan by a polygonal mirror rotated by a synchronous motor. If these movements are perfect and the mirrors are perfect then everything is fine, but things are not perfect. Any dirt or discontinuity throws off the calibration. Any stickiness in the motions cause unstable readings. Shock or vibration to the unit can cause angular accelerations to the rotating mirror. Any movement in the direction of scanning will change the time of the shadow and therefore change the size reported. Movement toward or away from the mirror can change the size reported because the beam is not perfectly the same size throughout its length nor is it perfectly parallel throughout its sweep. The only motion allowed is perpendicular to the plane of the scanning. Finally, like any digital electronic device, it can be affected by strong magnetic fields or line surges.

Wavelength of light

There is the problem that no optical scanning system can accurately resolve any finer than the wavelength of the light being used. This is the same problem that limits the magnification available with an optical microscope. If a Helium-Neon laser is used, then the wavelength of light is about 23 millionths of an inch.

To get around these problems, the laser based scanning systems presently on the market take many readings and average them together to get a reasonable repeatability. Since the individual scan results will show a very high degree of randomness, a gaussian distribution can be expected. As a result, the average of all these scans will generally be well within the manufacturers specifications but not always.

Our tests of the most popular laser based scanning unit now on the market showed an expected accuracy of 45 millionths of an inch.

Poor fixturing

Much of the fixturing that we have seen does not properly hold the wire sample. Please remember that almost all wire samples will have some curl. The collet and V-block arrangement does not assure that this curl does not cause a cosine error and worse still does not even keep the cosine error constant. In almost every case, this type of fixturing ends up giving an out-of-round reading much larger than is produced by any other measuring method. Actually, however, what is being read is not an out-of-round condition, but a varying cosine error.

This is not to say that laser based scanning measuring units are useless. They are a vast improvement over hand held micrometers and have a further advantage of being able to continuously monitor the size of wire or other parts which are in-process. One simply has to understand the limitations of these instruments—and of any other instruments for that matter—and apply them accordingly.

Weighing

The weighing of a long sample of wire will usually give the most consistent results. This is because most of the errors along the length of the sample cancel out. Accuracies for a .003 inch diameter wire can be as good as 6 millionths of an inch if sample preparation is done very carefully. The two biggest drawbacks are the length of time required to make the test and the fact that an out-of-roundness measurement will have to be made on some other piece of equipment.

Resistance

Measuring the diameter of a wire by measuring the resistance of a measured length of a sample may seem tempting especially for magnet wire or heating wire. Unfortunately, this method produces the worst consistency of any method with which I am familiar. The reason is that resistance is measured by how much current flows in the wire and a very small anomaly can have a large effect on the flow of current. Think of it this way. If you put a certain amount of water pressure into a given length of garden hose, you could measure the size of the hose by the amount of time it took to fill up a bucket. Pinching the hose only slightly in only a small place, however, would drastically change the time it took to fill the bucket and thus the calculated size. Further, a rough inner surface of the hose would restrict the flow of water just as a change in the bulk resistivity of the metal will restrict the flow of current in a wire. Under most circumstances, I do not recommend the use of resistance of a wire sample to measure the diameter of a wiredrawing die.

Direct hole measuring methods

As noted above, measuring a wire sample is usually the preferred way to measure a wiredrawing die, but there are some cases where direct hole diameter measurements are used.

Air gaging

The size of the hole in the drawing dies may be measured by the pressure drop from passing a stream of air through the hole. This method can give at best an accuracy of 40 millionths of an inch for small sizes. It also has to be recalibrated frequently at or very near to the size being measured. In other words, the drift and linearity are both poor. The main advantage is that it is relatively fast and requires little operator skill, so it is mainly used where a large number of dies with wide tolerances have to be measured.

Mechanical probes

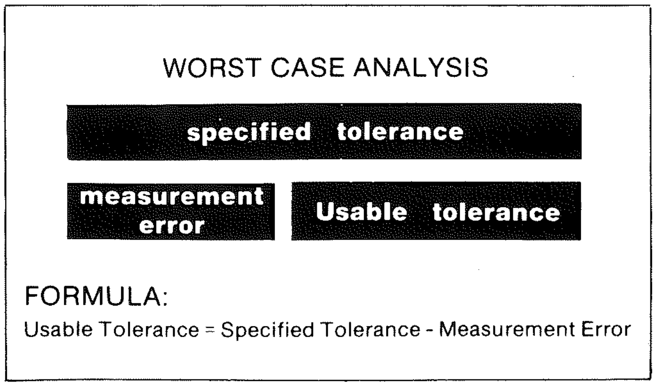
Mechanical probes with either mechanical or LVDT readouts are available for measuring larger dies— usually above 0.04 in. dia. There is a wide range of accuracies claimed by several manufacturers, but accuracy is usually no better than 0.0001 in. The main advantage is ease of use if the gage is fixtured properly. The main disadvantage is that the probe usually slides into the bore which quickly wears the probe.

Optical methods

There are several methods based on magnifying an image of the hole and either viewing it directly as in a microscope or projecting it onto a screen as in an optical comparator. All these methods are relatively quick but have a problem that accurate focus is required to obtain good readings. Accuracies depend upon what the magnification is and how well the optics are calibrated. All these methods would be considered "quick and dirty" and so would not be recommended for general use.

What is the effect of all this?

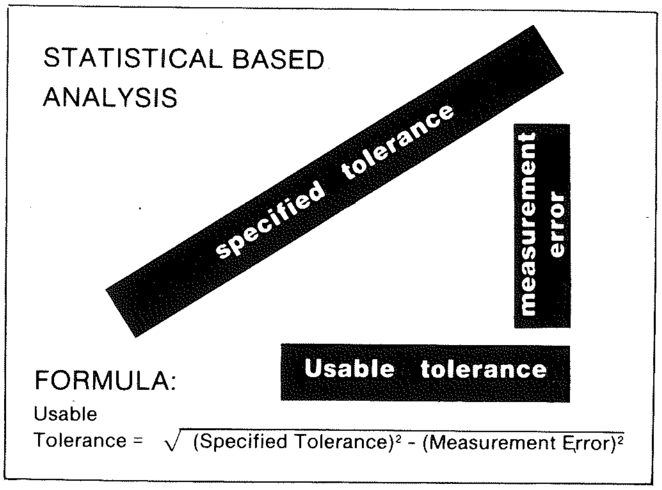
By now it should be obvious why we are concerned with measuring methods and errors. Measuring capability in a large way determines how small our tolerances can legitimately be. In Fig. 6 we can see the effect on a "worst case" basis. It shows simply that if we take the variability that our process delivers, we have to add our possible measurement error to it to see what our overall tolerance can be. Fig. 7 shows the same idea but in a statistical form instead of worst case. If we know our process capability to a certain sigma limit and our measuring capability to the same sigma limit, then we take the square root of the sum of the squares which gives us the final tolerance capability to the same sigma limit. The statistical method gives a more optimistic number, but, of course, it requires good statistical data for the calculation to be valid. In any case, it is obvious that if your customer has a very demanding tolerance and the measuring instrument uses up a lot (or all) of that tolerance, you have a problem. Also, a poor measuring instrument may cause you to reject good material from a vendor, or worse yet, accept bad material. And, of course, your vendors face the same measuring limitations that you do, so you cannot arbitrarily tighten your tolerances to your vendor.



FORMULA:

Usable Tolerance = Specified Tolerance - Measurement Error

Fig. 6. Effect of measurement errors.



FORMULA:

Usable Tolerance = $\sqrt{(\text{Specified Tolerance})^2 - (\text{Measurement Error})^2}$

Fig. 7. Effect of measurement errors.

WORST CASE ANALYSIS

Reading error at calibration	+/-20 microinches
Reading error at measurement	+/-20 microinches
Error of standard	+/- 5 microinches
Drift	+/- 2 microinches
Non-linearity	+/-10 microinches
Total Possible Error	+/-57 microinches

Fig. 8. How to analyze the capability of a measuring instrument.

When analyzing measuring capability, you have to consider several factors as shown in the worst case analysis in Fig. 8. Let us look at each of these items. The first two items are the result of the level of precision. You may wonder why the reading error is listed twice. If the calibration reading appears to be correct, how can there be an error? Simply put, you can get the right reading by mistake. You can quickly show this by the following test. Calibrate your instrument and then take a number of readings of a given sample. Then recalibrate and take more readings of the same sample. Repeat this experiment a number of times. When you analyze the data statistically, you will find that the variation between the averages of the sets of readings is the same as the variation between individual readings within a set of readings.

And so we can see that, indeed, the calibration readings also experienced errors. The third item, the error of the standard we are using to calibrate with, comes from either the manufacturers data or from a metrology lab and will depend on how good his standards and equipment are. The drift has to be estimated from the data supplied with the measuring instrument as applied to your environment. Finally, errors due to offset and linearity are calculated from the data supplied by the manufacturer of the measuring equipment. In the worst case analysis, these numbers are all added to get an expected error.

It is unlikely that all the items listed above will be off their fullest possible amount and in the same direction at the same time. Therefore, we can legitimately use the statistical analysis as shown in Fig. 9, although we have to make sure that the individual values are statistically correct. In this case, we take the square root of the sum of the squares to get the total expected error. You will again note that this is a more optimistic number than was obtained in the worst case analysis.

STATISTICAL BASED ANALYSIS

(Reading error at calibration)^2 = 400
(Reading error at measurement)^2 = 400
(Error of standard)^2 = 25
(Drift)^2 = 4
(Non-linearity)^2 = 100

Sum of Squares = 929

Total Statistically Expected
Error = +/- $\sqrt{929}$ = +/- 30.5 microinches

Fig. 9. How to analyze the capability of a measuring instrument.

One thing that these analyses should point out is that there are several sources of error that would not be obvious during a demonstration of a new piece of measuring equipment. Unless you know about them ahead of time, you will not notice the error at calibration, the error in the standard or the linearity errors. You may not even notice drift unless the demonstration is a long one. It is important to analyze both your needs and the true capability of any measuring equipment that you intend to use.

Summary

There is not really any such thing as "good" or "bad" measuring equipment. There are only good and bad applications of measuring equipment. It would be nice if I could tell you exactly what measuring equipment to use, but only you can decide what is best for your particular situation. I hope that I have given you the information necessary so that you can make good decisions. Above all, remember that the quality of what you manufacture depends to a large extent on the quality of your measuring equipment. An expensive measuring instrument that exactly fits your situation costs you only once, but a cheap instrument that does not do the job will cost you forever.

Fort Wayne Wire Die, Inc.