INTRODUCTION

WHAT MAKES UP A MEASUREMENT

When a piece of gaging equipment is not providing the expected results, it's common practice to find fault with the gage itself. However, this approach will often fail to find the problem, or may only find only part of it, because the instrument is only a portion of the total measuring system. Understanding what makes up a measurement is an important step in knowing what to look for when troubleshooting measurement problems.

There are at least five parts in a complete measuring system. Each one plays an important part of the measuring process and if one part fails then the measuring result is apt to fail also.

A reference standard used when the system is set up or checked for error. This could be a master in comparative gages or the lead-screw in a micrometer.

The work-piece is another element of the measurement process. Variations in geometry and surface finish of the measured part directly affect measurement system's repeatability. These part variations are difficult to detect, yet can sometimes manifest themselves as apparent error in the measuring system. For example, when measuring a center-less ground part with a two-point measuring system, certain form errors will not be detected.

The instrument is a key component of the process. It should be selected based on the tolerance of the parts to be measured, the type of environment and the skill level of the operators. All measuring instruments are not created equal. While different style gages be measuring the same dimension, different techniques may produce slightly different results – as sometimes seen in the differences between contact and non-contact measurements.

Operators of the gage are actually integral the process. Failure to adequately train operating personnel will result poor measurements. Even the operation of the simplest of gages, hand tools to air gaging, requires some operator training for adequate results. Very important to the process is operator, assuming responsibility for maintaining the instruments. Checking for looseness, parallelism, nicks and scratches, dirt, rust is absolutely necessary to ensure system performance.

Finally there's the environment the gage is used in. Thermal factors such as radiant energy, conductive heating, drafts and room temperature differentials can significantly impact gage system performance. And, again, dirt, oil, machine chips are the key enemies of gaging.

Understandings what the measurement process consists of will help you consider all the factors influencing the accuracy of the measurement being performed, and, may point to sources of poor gage performance.

MEASUREMENT OR GAGING?

Often the terms "gaging" and "measuring" are used interchangeably. There are times when gaging is appropriate, and other times when measuring is the way to go. There is a difference.

Measuring is a process, in which the direct-reading inspection instrument consists of (or incorporates) a scale—a continuous series of linear measurement units (i.e., inches or mm), usually from zero up to the maximum capacity of the instrument. The work piece or part under consideration is compared directly against the scale, and the user counts complete units up from zero, and then fractions of units. The result generated by "measuring" is the actual dimension of the work piece feature. Examples of measuring instruments include steel rules or scales, vernier calipers, micrometers, and height stands. CMMs might also fit in this category.

Gages, in contrast, are comparative instruments. The measurement units live not on a scale, but off-site (in a calibration lab somewhere), and a master or other standard object acts as their substitute. The work piece is directly compared against the master, and only indirectly against the measurement units. The gage thus “measures” not the dimension itself, but the deviation between the mastered dimension (i.e., the specification), and the work piece dimension.

Gages fall into two main categories: "hard," and "variable." "Hard gages” —devices like go/no-go plugs and rings, feeler gages, and non-indicating snap gages—are not easy to generate numerical results from. They usually tell the user only whether the part is good or bad. Variable gages incorporate a method for sensing and displaying the amount of variation above or below the established dimension. All dial indicator and comparator gages meet this description, as does air and electronic gaging. The measurement result generated by a variable gage on an accurately sized part is generally 0 (zero), not the dimension. Because of modern industry's need for statistical process control, variable gaging is the norm, and there are few applications for hard gaging. Though hard gaging still has its place for some machine set-up, large tolerances or presence of certain part features.

Variable gaging may be further subdivided into fixed and adjustable gaging. Fixed variable gages, which are designed to inspect a single dimension, include mechanical and air plug gages, and many fixture gages. Adjustable variable gages have a range of adjustment that enables them to be mastered to measure different dimensions. Note that the adjustable range of the gage is not the same as the measuring range of the gage. An adjustable snap gage may have the capability to be adjusted any where within a 0 to 1” measuring range. However it would be impractical to constantly re-master the gage to inspect a mixture of .250” and .750” parts. (This would be no problem for most "measuring" instruments, however.) Almost all indicator gages will be of the adjustable variety.

Because of its relative mechanical simplicity, fixed gaging tends to hold calibration longer, and require less frequent maintenance and mastering. It is often easier and quicker to use than adjustable gaging. But it is also inflexible: once a production run has finished, a shop may find it has no further use for a gage designed solely to inspect IDs of 2.2370", ±0.0002".

Where production runs are smaller, or where throughput is not quite so important, adjustable gaging often makes more sense. The range of adjustability allows a gage to be adjusted toward a new inspection task after the initial one is completed. The adjustable bore gage being used today to measure IDs of 2.2370", ±0.0002" may be used to measure IDs of 1.0875", ±0.0003" next month.

Fixed gaging therefore tends to be economical for inspection tasks that require high throughput, and for production runs that involve many thousands of parts, and that last for months or years. Adjustable gaging tends to be appropriate for shorter production runs, and for smaller shops in general.

Similar issues apply when comparing "gaging" and "measuring." Gaging tends to be faster, both because it is less general-purpose in nature, and because the operator need observe only the last digit or two on a display, rather than count all of the units and decimals up to the present dimension. Because of its generally much shorter range, gaging can also be engineered for higher accuracy (resolution and repeatability) than measuring instruments. For anything resembling a production run, gaging is almost always required. But where single part features must be inspected, measuring devices tend to make more sense. In practice, most shops will find they need some of both types of devices.

GAGING PERFORMANCE

Many times gages and measuring instruments are taken for granted. If they worked yesterday then they will work today. As a machine operator or inspector, you must assume much of the responsibility for gaging accuracy. Whenever a gage has not been in frequent use, make sure you follow these basic steps:

- Providing the measuring display (dial indicator, digital indicator or other sensor) has been checked for calibration, repeatability and is free running, look over the way it is mounted to the comparator frame or gage. Inspect for any looseness and correct.
- Check for looseness of play in gages posts, bases, clamping handles, fine adjustment mechanisms and anvils. Don’t assume that the performance of the indicator out weighs the errors introduced by an un-tightened anvil.
- When using portable or bore gages, be sure to check adjustable or changeable contacts to be sure they are secure.
- When gage backstops are to be used and relied on, make sure they are also clamped tight in the proper location.
- The sensitive contact points on many portable gages and bench comparators are tipped with wear-resisting tungsten carbide, sapphire or diamond inserts. Examine them under a glass. If they are cracked, chipped or badly scored, their surface conditions may prevent accurate or repeatable readings. They may even scratch the work.

- If opposing anvils are supposed to be flat or parallel, check them with the wire or ball test. By positioning a precision wire or ball between anvils, you can read parallelism (as seen by variation) on the indicator simply by moving the wire/ball front to back and side to side.
- One of the easiest chores to neglect is regular cleaning of indicating gages and bench comparators. Clean all such instruments thoroughly at each use. Also, be sure to rustproof exposed iron or steel surfaces.
- Take the same steps to ensure the reliability of master discs and master rings as you would for gage blocks. Examine them for nicks and scratches and the scars of rough handling. And handle them as you would gage blocks, as well.
- Finally, if you see a sudden shift in your process during the day, these same basic steps should be part of your troubleshooting routine. Don't assume the part has changed dramatically. Re-master and re-measure. Don't automatically assume your gage is correct just because it has a calibration sticker.

TEMPERATURE AND GAGING

Thermal effects are becoming one of the largest sources of gaging error. Dirt, as a gaging problem, is either there, or it isn't. But everything has a temperature -- even properly--calibrated gages and masters. The problem arises from the fact that everything else has a temperature too, including the air in the room, the workpiece, the electric lighting overhead, and the operator's fingers. Any one of these "environmental" factors can influence the reading. And, as tolerances become tighter and tighter, the effects of temperature become more significant.

Why is temperature such a critical concern? Because most materials expand with heat, and they do so at differing rates. For every 10° F rise in temperature, an inch of steel expands by 60 millionths. Aluminum expands at more than twice that rate, and tungsten carbide at about half. This becomes a major issue if you are trying to measure a 2-inch aluminum work piece with a steel-framed snap gage and tungsten carbide contacts, after the workshop has just warmed up to 7 degrees. Add to this a part that has just been machined and is 10° F hotter then the master. This is why it's critical to keep the gage, the master, and the work piece all at the same temperature, and hopefully made from similar materials.

Gage and master must be kept together, to ensure that they "grow" in together and to permit frequent re-mastering. Work pieces must have sufficient time to reach ambient temperature after machining, or after being moved from room to room. The operator should avoid handling the gage, master and work piece more than necessary.

Care must be taken that sources of heat and cold in the room do not intrude on the process. Incandescent lighting, heat and air conditioner ducts, even a shaft of direct sunlight through a window can alter a whole series of measurements. Keep things at the same "altitude" in the room, to avoid the effects of temperature stratification.

As tolerances tighten, additional measures become necessary. Work pieces should be staged on a heat sink beside the gage and should be handled with forceps or gloves. A Plexiglas shield may be required to protect the gage from the operator's breath.

DIRT AND GAGING

Cleanliness is another step in improving accuracy in gaging. Probably every machinist is at least nominally aware that dirt can interfere with the ability to take accurate measurements. The importance on the issue cannot be over-emphasized, and even a conscientious user needs to be reminded of this important factor.

Leave your gage out of its box for a few hours. Then check it for zero setting. Next, clean the measuring surfaces and blow off the lint. Check the zero setting again. You will probably find a difference of about 0.0005" due to dirt on these surfaces.

Or, try this one: Leave a clean master disc, marked 0.7985"XX unprotected for a number of hours on a work bench ion the shop. Then, taking special pains not to touch its measuring surfaces, bring it into a temperature controlled room and let it cool off before measuring it with an electronic comparator. It will not be unusual to see the needle off the scale, meaning that the master plus dirt was more than 0.0003" larger than the nominal 0.7985" setting. Carefully and thoroughly clean the master with solvent and measure it again. The reading should come very close to it's marked dimension.

And finally, clean the master again, using the time-honored machinist's method of wiping it with the palm of the hand. This time, measuring it again could show an indication of the size increasing up to +0.000013". Half the normal gage tolerance is lost by "cleaning" it with the palm of your hand. (Some slight error may also have been introduced through expansion of the master due to conductive heating from the hand).

See how dirt in invisible quantities can skew a measurement, both on the contacting surfaces of the gage itself and on the work piece or master. Now picture the gage in your shop: Is it living in an oil-and-chip-filled apron of a lathe or screw machine, or perhaps sharing the pocket of a shop apron with pencil stubs, pocket lint and what have you?

Aside from simply getting in the way of a measurement, dirt also impedes accurate measurement by increasing friction in a gage's movement. Drag may prevent a mechanism from returning to zero, and every place that friction must be overcome represents a potential for deflection in the gage or the setup.

Next time you have a serviceman in to work on a gage, watch him. Chances are, the first thing he does is clean the gage, whether it is a simple dial indicator or a Coordinate Measuring Machine. If you take only one thing away from this column, this should be it. Eliminate dirt as a possible source of error before attempting to diagnose a malfunctioning gage.

SETTING A GAGE REFERENCE POINT - ZEROING

When we talk about using comparative gaging, it is required to "zero out the gage" prior to making any measurements. Zeroing sets a reference point from which all subsequent measurements are made. If a gage has been allowed to drift from zero, it will introduce error into the measurement process. So it's important to "Zero," often.

Why do gages shift their zero point? There are probably as many reasons as there are types of gages. But the top reasons include all the items just discussed: wear, temperature effects, loose gaging components and dirt. It's important to check zero as often as needed, so that you feel comfortable with the measurement process.

Basic instruments like micrometers or calipers use their scales as the reference. With a vernier micrometer, verifying the reference point is straightforward. Close the contacts together and read the vernier scale. The scale should indicate zero. If it doesn't, you can be sure that every measurement from then on is going to be off by the amount indicated on the scale.

The best thing to do is correct this error is by adjusting the micrometer to make it read zero with the contacts closed. Most micrometers, both friction and ratchet drive types, provide instructions to adjust this zero point. Follow the instructions carefully and you will have your micrometer zeroed out in a matter of minutes.

Likewise, a vernier or dial caliper can be checked by bringing the contacts together and holding the jaws up to a light. You should not see light passing through the jaw surfaces. Look for gaps or taper conditions that indicate a worn jaw. If the jaw passes inspection, check for the zero readings. On a vernier caliper you will need to read the lines, while on a dial caliper the indicator should read zero. Both can be adjusted to read zero.

Digital hand tools are easy to zero. Close the jaws and press the zero button. That's all there is to it. The instrument does this important little task electronically.

Comparison type measurement hand tools such as snap gages, gage stands, bore gages, etc., may be a little trickier, but they also need to be zeroed regularly. The process is slightly different, but the end result is the same. With this type of gage the zero point is actually a reference dimension to which dimensions on the parts will be compared. An ID, for example, will be shown to be greater or less than the zero (reference dimension).

For dial indicators, the method is to mechanically adjust the dial indicator on the master so that it is in its midrange, and lock it firmly into place. Then loosen the bezel clamp and turn the dial so that the indicator hand lines up with the zero on the dial.

Something else to remember is that setting to zero this once does not end the process. Take the master out and replace it a number of times in the gage, and check for zero again. A bit of dirt may have been introduced in the initial setting and repeating the process a number of times will help instill confidence in the set-up. Usually you want to have a dial indicator reading repeat its zero setting to within a half of a grad or so, or a digital readout should be to within one count. This varies a little depending on the gage and the resolution, but in any case we are assuming that the gage has already been checked for repeatability performance.

You should also know that there are instances where you may want to set your gage to a value other than zero. This makes it possible to correct for a known error in the master or to use a different size master for measuring the part. For example, if the master is +.0002" larger than the nominal dimension for the part, you would set the dial on the indicator to +.0002" instead of zero. Now if you have a perfect part, the gage would read 0.0" when the part is measured. Electronic dial indicators and amplifiers, in addition to zeroing buttons, usually have master deviation functions to do the same type of correction.

Zeroing the gage is the very foundation of good measurement practice, but we know that most gages are not zeroed often enough. If too many measurements have been made or too much time has elapsed since the gage has been zeroed, measurements will all be biased by zero shift. An extreme solution would be to zero, measure, and zero for every part. This would be overdoing it in most cases. On the other hand, zeroing once a day is probably too little. Generally speaking, once an hour is just about right, but the application itself should dictate the zeroing frequency.

CHOOSING THE RIGHT GAGE FOR THE JOB

Like every other function in manufacturing operations, inspection is subject to management's efforts at cost control. It's good business sense to try to maximize the value of every dollar spent. Issues as diverse as personnel, training, warranties, throughput requirements, manufacturing methods and materials, the end-use of the work piece, and general company policies on gaging methods and suppliers may influence both the effectiveness and the cost of the inspection process.

For example, what's the ultimate cost of a bad part passing through the inspection process? It could be just a minor inconvenience to an OEM customer—maybe a two-second delay as an assembler tosses out a flawed two-cent fastener and selects another one. On the other hand, it could be a potentially disastrous equipment malfunction with expensive, even fatal, consequences. Even if the dimensional tolerance specifications for the parts are identical in both instances, management should certainly be willing to spend more on inspection in the second case to achieve a higher level of certainty—probably approaching 100 percent. One disaster averted will easily pay for the more expensive process in lawsuits avoided, lower insurance premiums, etc.

Many companies have achieved economies by moving inspection out of the lab and onto the shop floor. As this occurs, machinists and manufacturing engineers become more responsible for quality issues. Luckily, many gage suppliers are more than willing to spend time helping these newly assigned inspection managers analyze their functional requirements.

One could begin by comparing the hardware options. Let's take as an example a "simple" OD measurement on a small part. This inspection task could conceivably be performed with at least seven different gaging solutions:

1) Surface plate method, using V-blocks and test indicator
2) Micrometer
3) Purpose-built fixture gaging
4) Snap gage
5) Bench-type ID/OD gage with adjustable jaws
6) Hand-held air ring or air fork tooling
7) A fully automated system with parts handling.

(Actually there are many more solutions available, but let's keep it "simple.") Between these options there exists a price range from about $150 to $150,000. There are also differences in gage accuracy, operator influence, throughput, data output, and on and on. It's confusing, to say the least.

A better approach is to first define the functional requirements of the inspection task, and let that steer one toward the hardware that is capable of performing the tasks as identified. In order to do this, the end-user should consider the following factors:

- Nature of the feature to be inspected. Is it flat, round or otherwise? ID or OD? Is it easily accessible, or is it next to a shoulder, inside a bore, or a narrow groove?

- Accuracy. There should be a reasonable relationship between job tolerance and gage accuracy resolution and repeatability—very often on the order of a 10:1 ratio. A requirement for statistical GR&R (gage repeatability and reproducibility) testing may require 20:1. But always remember:

- Inspection costs. These increase sharply as gage accuracy improves. Before setting up a gaging operation for extremely close tolerance, verify that that particular level of accuracy is really necessary.

- Time and throughput. Fixed, purpose-built gaging may seem less economical than a more flexible, multi-purpose instrument, but, if it saves a thousand hours of labor over the course of a production run, it may pay for itself many times over.

- Ease of use, and training. Especially for shop-floor gaging, you want to reduce the need for operator skill and the possibility of operator influence.

- Cost of maintenance. Can the gage be maintained, or is it a throw-away? How often is maintenance required, and who's going to perform it? Gages that can be reset to a master to compensate for wear are generally more economical over the long run than those that lose accuracy through extended use, but may require frequent mastering to ensure accuracy.

- Part cleanliness. Is the part dirty or clean at the stage of processing in which you want to measure it? That may affect labor requirements, maintenance, and the level of achievable accuracy, or it might steer you toward air gaging, which tends to be self-cleaning.

- Gaging environment. Will the gage be subject to vibration, dust, changes in temperature, etc.?

- "Mobility." Are you going to bring the gage to the part, or vice versa?

- Parts handling. What happens to the part after it's measured? Are bad parts discarded or reworked? Is there a sorting requirement?

- Workpiece material and finish. Is the part compressible? Is it easily scratched? Many standard gages can be modified to avoid such influences.

- Manufacturing process. Every machine tool imposes certain geometric and surface finish irregularities on workpieces. Do you need to measure them, or at least take them into consideration when performing a measurement?

- Budget. What do you have to work with?

All of these factors may be important when instituting an inspection program. Define as many as you can to help narrow the field, but remember that help is readily available from most manufacturers of gaging equipment—you just have to ask.

REFERENCE STANDARDS

HANDLING OF STANDARDS

Quality Assurance can only be as good as the measuring tools it relies on. It should be obvious that if you spend tens of thousands of dollars on a measuring machine, you need to protect this investment with routine maintenance and calibration. The same is true for hand tools and gages which are the nervous system of a manufacturing operation's quality system.

So dial indicators, hand gages and their masters need to be regularly calibrated. Checking these tools against recognized standards assures their reliable performance and provides for traceability when nonconformity does rear its ugly head in the manufacturing process. As soon as the manufacturing team buys into this concept and a program of regular calibration has become a way of life, your company will have taken a big step forward on the road to cost reduction and profit enhancement. That's the big picture.

If your quality assurance program is working well, it means everyone is taking care of the little details that are ultimately so important.

Newly calibrated gages, etc., are generally packaged and transported back to the floor with great care. But what about the tools and artifacts that are being sent back to the calibration room to be checked again? It's very important to remember that even though these gages are out of service, they are still precision measurement devices. As such, they need to be handled accordingly.

Very often we will see gaging come back for re-certification in the condition pictured. Or, even worse, they will be all thrown into a box with nothing to prevent them from banging together.

Under a microscope, one good scratch on an XX master ring can look like the Grand Canyon, ruining an otherwise good master. And we discover these Grand Canyons with alarming frequency at our Precision Measurement Center where thousands of master rings and discs are measured in the course of a year. Many of these scratches result from the sort of treatment that the rings in the photo are subjected to.

If you don't think those rings are being abused, look again. For the most part this packaging was carefully applied, but notice the wire on the tags. Now, in some cases there may be some plausible excuse for the marking of the rings this way. Maybe they are badly worn and are being sent back to be lapped and chromed back up to specification. However, even though the wire is soft, it still will mark and potentially scratch the part. Therefore, this type of packaging is never recommended.

A natural alternative is to attach an identifying tag with string. But don't do it! String tends to absorb rust-causing moisture. Stamping them with tool numbers is not the answer either. The stresses created in the metal can sometimes ruin a master.

However, don't give up; there are ways to mark the masters without risking damage. Some acceptable ways of identifying a master for shipment and inspection are to mark them with paint or a permanent marking pen. Or include a sheet of paper that identifies the ring by its etched dimensions on the side. Even a sticky tag is a good temporary method of getting the ring identified until it reaches the source of recalibration.

Of the rings and discs that pass through our measurement center that have been sent in for annual size certification, surprising numbers have had to be reworked or even scrapped because of improper packaging. A ring needs to be sufficiently protected whether it is traveling across the shop or across the country. It should be protected with an oil and plastic dip, individually wrapped and sturdily packaged.

The safest policy is to have one or more individuals trained in the proper handling, packaging and transporting of hand tools and masters for recalibration. This is a simple little detail that can pay for itself many times over during the course of a year. Most gaging equipment suppliers would be happy to provide you with the guidelines you need to bring this little picture into sharp focus.

MICROINCH REVOLUTION

Those growing up in the manufacturing industry have seen tolerances of machined parts shift from thousandths to "tenths," and we had to adjust both our production techniques and our QC measurement methods. As ever more technical products make the need for precision even more profound, a similar shift is now under way, toward millionth-measurements. For this gaging methods will have to change radically.

Previously, we focused much of our attention on the gage itself: as long as the instrument was designed to the required degree of accuracy and maintained properly, we could usually get by, even at the "tenths" level. Now that we're trying to measure tolerances of 50, 30, or even 20 millionths, we must shift our focus to the measurement process and the environment in which it takes place. Where temperature and cleanliness were formerly somewhat abstract issues, they now become essential concerns.

According to the old gage-maker's 10:1 rule of thumb, when measuring tolerances of 30 millionths, the gage should demonstrate repeat accuracy of 3 millionths. But consider this: a difference of 1°F between the part, the master, and/or the gage can introduce an error of 3 millionths. In other words, if we don't control thermal influences, we give up all hope of repeatability.

Microinch gaging therefore must be performed in a controlled environment -- a special room that is thermally insulated from the shop floor. Temperature should be kept as close to 68_ as possible, and changes must not exceed 2_ per hour. When a part comes in from the shop, it should sit for several hours on a heat sink (a large steel plate), to bring it into equilibrium with the master and the gage before being measured. Even with all of these precautions, the gage should be mastered frequently.

The gage should be protected from the operator's body heat, and his breath, by a clear plastic shield or full enclosure. The operator should not touch the parts or masters directly: insulated tweezers, gloves, or similar measures should be employed.

Elaborate measures are also required to combat the problem of contamination. Relative humidity in the room should be kept below 50% to inhibit the formation of rust. Parts must be thoroughly cleaned of dirt and even thin oil films prior to gaging. The choice of cleaning solvent will vary with the application and may require some trial and error to ensure that the solvent itself doesn't leave a film. It will be necessary to regularly clean the entire gaging area, plus the gage and masters, to remove dust, skin oils, etc. Even the choice of furniture upholstery and the clothing worn by operators must be considered: natural fibers shed more dust than synthetics. The room should have an air lock, and unqualified personnel should be prohibited from entering. If there is a computer printer in the room, it should be in an enclosure, and single-sheet paper feeding should be used: paper dust may released into the air when tearing continuous forms along their perforations.

At microinch tolerances, dimensions change so readily that it may be more practical to check part relationships (i.e., clearance) than absolute dimensions. "Match gaging," which is sometimes associated with imprecise process control, can be the best and easiest way to ensure that parts will fit together with the required clearance.

Surface finish and part geometry become critical parameters at the microinch level, and for any degree of repeatability to be possible, it is necessary to use witness marks, or some other method to ensure that a part is always measured at the same location. The whole subject of mastering, calibrating, and certifying a gage to millionths is important enough to deal with at length in a future column.

Even with sophisticated gages that are fully capable of the task, measuring to millionths remains a challenge. It requires thorough planning, careful selection of conscientious personnel, and significant investments in training and facilities, as well as a good understanding of all the variables that can affect microinch dimensions. It may be tempting to just buy the new gage and give it a go, but I can guarantee you'll spend more time figuring out your problems and ways to fix them than you would by doing it right in the first place.

MECHANICS OF MILLIONTH MEASUREMENT

In a recent column we looked at some of the challenges inherent in measuring parts to microinch tolerances. We discussed the need for a climate-controlled environment and absolute cleanliness, but we've only scratched the surface (so to speak). Special attention must also be paid to the selection of the gage and readout, and to mastering.

If you're checking parts for tolerances of 10 microinches, or checking gage blocks, rings and discs to millionths, you'll need resolution (i.e., minimum grad value) of 1 microinch, or maybe even 0.1 microinch, on the gage readout. But beware of excessive magnification. Some gage manufacturers create the appearance of microinch accuracy by supplying an electronic amplifier, with units reading in millionths, on a garden-variety gage. Because the average shop-floor gage is mechanically repeatable to only 50 millionths or so, what you really get is a highly magnified look at the gage's repeatability error. The resolution of the readout should accurately reflect the precision (i.e., repeatability) of the gage itself. This can be checked by repeatedly measuring a part under controlled conditions. If the reading varies by .000005" or more between trials, the gage may be incapable of handling microinch inspection duties.

When measuring high-accuracy IDs, gages typically contact the workpiece with up to 4 ounces of gaging force. At microinch tolerances, this can produce measurable deflection of the jaws. That deflection may be unavoidable, so repeatability demands that it remain constant from one trial to the next. A frictionless mechanism, such as a reed spring arrangement, is therefore essential to maintain the gaging force constant to within 1/2 gm.

Normally, we rely on a master to assure the accuracy of a gage. But if we're using the gage to measure a master, we have to go one step further and refer to certified gage blocks to master the gage. This is relatively straightforward for outside measurements, but more complex for inside measurements.

There are two accepted methods: In the first, a single gage block or a stack of blocks is used to set a pair of caliper blocks at a precise distance. The blocks are held together with clamping rods, with the caliper blocks extending over the gage blocks on both sides. (See Figure 1.) The gage is mastered to the distance between the caliper blocks, checking at both ends for parallelism error. Ball feet may be snapped onto the block assembly: this makes it easier to move around on the table using insulated forceps or other tools, and helps to minimize the transfer of heat from the operator's hands.

In the second method, two or more blocks are wrung to a true square, with enough overhang on the topmost block to fit over the gage contacts. A second set of blocks is wrung against an adjacent edge of the square to check for squaring error. (See Figure 2.) This setup is less subject to parallelism error than the first method. In both methods, the operator should wait at least three hours after assembling the blocks, to give temperatures a chance to normalize.

When measuring master rings, it is necessary to account for geometry errors, as well as surface finish, scratches, waviness, and other microinch imperfections. Measure Class XX masters (tolerance = .00002" for sizes between .029" and .825") at a depth of 1/16" in from both ends, and in the middle of the ring. This avoids the bellmouth conditions likely to exist near the ends, and detects most barrel-shape, hourglass, and tapered conditions.

For Class XXX masters (tolerance = .00001" for sizes between .029" and .825"), the drill is even more rigorous. Confine all measurements to a 1/4" tall band in the center of the ring, and take a total of six measurements: at the top, middle, and bottom of the band, in both north/south, and east/west orientations.

The point here is not to find and discard masters that show variation of a millionth or more. When working at the microinch level, a certain degree of uncertainty is inevitable. The objective is to minimize the uncertainty that the master contributes to the overall measurement process.

TRACEABILITY

UNCERTAINTY

Look at a calibration certificate for a master or reference standard, and you'll likely see a statement that describes the accuracy or uncertainty of the measurement as being within a certain range. Very often these terms are used interchangeably, but in fact, accuracy and uncertainty describe two different philosophies of measurement.

Measurement is a process a process - more then just the gage. All of these factors impose a degree of variability on the process.

Uncertainty is quantifiable: it is the maximum amount of error observed under "normal" conditions for the master, the part, the operator, the environment, and the gage itself. Accuracy is the amount of agreement between the observed value and the actual value. Accuracy is the measure of perfection; uncertainty is the measure of deviation.

Uncertainty, which is error, arises from two types of conditions, referred to as random errors, and systematic errors. Random errors are usually defined as those to which statistical probability applies. Examples include the mechanical repeatability of the gage (actually the lack of repeatability); the condition of the part or master, variability in the gaging environment (e.g., thermal influences, dirt on gaging surfaces, etc.); and operator influences, such as how aggressively the gage is operated and how carefully gage blocks are wrung.

Systematic errors are uniform, and are not subject to probability. An error in a calibration certificate, for example, will impose a consistent error on all measurements. Errors in manufacturing specifications are also systematic, as are errors in prior measurements on which the current measurement depends. All sources of error are subject to testing and measurement, using documented scientific experiments.

The two types of error can be combined into a single estimate of uncertainty. Random errors are typically added in quadrature, as shown, because of the statistical unlikeliness of all random errors being in the same direction.

$R_T =$ (the square root of) $(R_1{}^2 + R_2{}^2 + R_3{}^2 \ldots R_n{}^2)$

Systematic errors are added directly, because these are known and consistent:

$$S_T = S_1 + S_2 + S_3 \ldots S_n$$

Total uncertainty is the sum of total systematic error plus a multiple—either 2 or 3—of total random error:

$$U_T = 2(R_T) + S_T$$

In any case, uncertainty is more then an educated guess, it's based on experiments that have been conducted to measure every known source of possible error. Therefore, the statement of uncertainty is scientific, quantitative, and justifiable. It should reference an independent, systematic testing program, employing controls, redundant measurements, and statistical analysis, and it should be supplemented by statistical data to verify results.

With today's high-magnification gages and tight-tolerance parts, these guidelines for uncertainty budgets are not always practicable. Understanding and application of master uncertainty have thus become essential, and need to be taken into account when purchasing gages and masters. For more detail on this subject, refer to NIST Technical Note #1297.

MEASUREMENT TYPES

HAND TOOLS

The basic micrometer is one of the most popular and versatile precision hand-held measuring tools on the shop floor. While the most common type is the outside diameter style, the principle can be used for inside diameters, depths and grooves. With so many options for holding the spindle and alternate contact points available, it's a tool to satisfy an endless number of measurement applications.

The biggest problem with micrometers is that measurements are subject to variations from one operator to another. There are two types of influences that contribute to this variation: "feel" or inconsistent gaging force, and subjective factors.

The micrometer is a contact instrument. Sufficient torque must be applied to the micrometer to make good positive contact between the part and the instrument. The only torque calibration in the human hand is the operator's "feel." What feels like solid contact to one operator, may not feel correct to another, so the readings will be different. In order to eliminate the "feel" part of the measurement, the designers of micrometers incorporated a ratchet or friction thimble mechanism. This is an attempt to assure more consistent contact pressure and eliminate the human influence.

The simplest thing to do is use a hand tool that has ratchet or friction drives to achieve more consistent gaging pressure. Or, in the case of the micrometer, the best way to obtain the most consistent reading is with an indicating micrometer. This type of micrometer combines the flexibility of range with the high resolution and consistent gaging force of a dial indicator.

The lower anvil of an indicating micrometer is actually the sensitive contact of a built-in indicator which provides readings (it's typically in 1µm/50µ" gradations) clearly and quickly with no vernier to read. Like the standard micrometer, you can adjust the spindle to the size needed and obtain a consistent gaging force when the master is set to zero on the dial indicator. Once established, the spindle is locked into position. Now the measuring tool begins to act like a gage by making measurements in a comparative mode. A retraction lever is also incorporated in the gage, making it easy to position the part for measurement quickly and to reduce wear on the contacts.

An indicating micrometer is a perfect gage for medium run, high tolerance parts. With this one gage an experienced operator can quickly set up the measurement process. Once the gage is locked in place, the indicating micrometer applies identical gaging pressure for each measurement, regardless of who is using it. The novice quickly obtains the same uniform high accuracy results as the experienced inspector regardless of differences in feel or what is known or not known about the part.

HAND TOOLS - CALIPERS

Although it has been around for a long time, the caliper is an extremely versatile and useful tool for making a wide range of distance measurements (both ODs and IDs). While micrometers are more accurate, they have a limited measurement range (typically several inches). The caliper, on the other hand, can span from two inches to four feet, depending on the length of the scale. External measurements are made by closing the jaws over the piece to be measured, while internal measurements are made by opening up the inside diameter contacts.

Three Types

There are three different types of caliper which may be found today in a machinist's tool chest.

Vernier. The vernier caliper was the original design and is still the most rugged. Graduated much like a micrometer, it requires the alignment of an etched scale on the vernier plate with an equally spaced scale running the length of the tool's handle. Skillful alignment of the tool and interpretation of the reading is necessary to achieve the measurement tool's stated accuracy.

Dial. A dial caliper is the second generation caliper. Similar to the construction of the vernier caliper, this style replaces the vernier scale with a dial indicator. The indicator is fixed to the moveable jaw, and engaged with toothed rack on the body of the unit. The dial, which is typically balanced (i.e., can move in either plus or minus directions from zero), may be graduated in either inch or metric units.

The dial caliper is a dual purpose tool for making either direct or comparative measurements. To make a comparison, first measure the reference dimension and set the dial indicator to zero. Then measure the compared dimension. The indicator will show how much the compared dimension varies from the original (plus or minus).

Another useful feature of the dial caliper are jaws which slide past each other to allow contact points or depth rod extensions to fit into narrow openings for small ID measurements.

Digital. In the last 20 years the digital caliper has made its way onto the shop floor. The latest designs provide many numerous electronic features which make the device easier to use, but add little in the way of cost. These include: easy switching between inch and metric units on the readout, tolerance indications, digital output to electronic data collection systems, zero setting anywhere along the caliper's range, and retention of the zero setting even when the caliper is turned off. With no moving parts in the readout, the digital caliper is exceptionally durable, standing up to some of the toughest manufacturing environments.

Proper "Feel". While the caliper is a versatile tool, it is not one of the most precise. Skill is required for positioning the tool and interpreting the measurement result. As the user develops his "feel" for the tool, his measurement results become more consistent.

While the digital caliper may take some of the guess work out of reading the measured value, it still requires skill on the part of the user to apply the tool properly to the dimension being measured. The jaws of the caliper must be square or perpendicular to the part. They are held firmly against the part, but not to the point of deflecting them. The part should be kept as close as possible to the frame of the measurement tool.

Knowing Its Limits. The rule of ten says that a measurement tool should have ten times more resolution than the tolerance of the dimension. Calipers typically read in 0.001" units. So if the tolerance is tighter than ±0.005", a micrometer (or some other higher accuracy tool) is the way to go.

The humble caliper is a surprisingly versatile tool for a wide range of general purpose distance measurements. With a little skill, you can make a fast direct measurement or comparison in seconds and move on quickly to your next important task.

DIAL INDICATORS

Dial indicators are as basic to the shop floor as micrometers and calipers. Just like these hand tools there are many variations to a dial indicator. There are different sizes, grad values, total measuring ranges, ranges displayed per revolution, Inch/metric and dial configurations. Determining which one to choose for the comparative process is fairly straightforward.

Dial graduation is the first thing to consider. Take the tolerance spread and divide it by ten. Then select the dial type with a minimum graduation closest to this figure. For example is the tolerance is +/-0.003", total tolerance is 0.006. Divide this by ten or 0.006"/10 = 0.0006". The typical closest grad value for this is 0.0005".

Industry specifications call for indicators in one of five standard sizes – from approximately 1.25" all the way to more then four inches. A small indicator might be needed for a tight spot in a fixture or for minimum weight on a portable gage. Larger indicators are useful where visibility is important.

Range per revolution is the amount of movement the spindle produces for one complete revolution of the indicator hand. Too low a range may mean counting a lot of revolutions while too long a range may make it difficult to measure within the tolerance range. The best approach is to have the tolerance cover one tenth to one quarter of the dial range.

Dial indicator specification call for the standard range of an indicator to be 2 ½ revolutions. This is more then enough for most comparative measurements. A longer-range indicator can be used in order to clear a part obstruction or add more versatility to the gage when used in a height stand as a long range measuring system. For these applications a revolution counter is a must to help keep track of the indicators position.

Once the indicator is selected, it's just as important to put it into service in the proper manner. First, mount your dial indicator correctly. The ideal method is to mount it from the back, using one of the optionally available lug or rack-type backs available from most suppliers. Mounting by the case or the stem is less desirable, because these components are part of the mechanism. Do not allow a sets-crew to bear directly on the stem--the stem will deform, interfering with the movement of the spindle in its bearings. If it is a requirement to stem must mount the indicator, it is essential to use a split bushing or a collet to distribute the clamping force evenly.

Worn or loose contacts can also cause incorrect readings, so it is essential to inspect them frequently for wear and tightness. Do not use pliers or a wrench--too much torque will distort the spindle, causing the mechanism to bind.

Replace contacts as soon as wear is detectable. If wear is rapid, consider changing to a harder material. Hardened steel contacts wear quickly when used against rough or abrasive surfaces and may also be affected by corrosive agents in the work environment. Chromium steel contacts offer better corrosion resistance, but are only marginally tougher than hardened steel. Tungsten carbide or diamond contacts are often the most cost-effective, even though they are the most expensive. They resist wear much longer, thus reducing the need for replacement parts and labor. More importantly, less wear means the indicator will produce fewer false readings.

If the indicator has been sitting idle for a while, the spindle may stick. Do not oil it. Work it in and out a few times by hand: chances are it will free up. Oil acts like a magnet for dust. Every time the spindle retracts into the case, it will pull contaminants into the indicator's precision movement. The oil, itself, will also harden with time, causing even more sticking.

The only part of an indicator that should ever be lubricated is the jeweled movement. Manufacturers typically use the point of a pin to apply a minuscule amount of watch-grade oil at this location (a drop of oil from a can would be too times too much).

Use a soft, lint-free cloth to remove dirt and oil from the spindle. Clean the crystal with soapy water, benzene, or a soft eraser. Replace scratched crystals and illegible faces. If the indicator looks like it is in poor shape, chances are it will be abused even more. If you keep it clean, it will be treated like the precision instrument it is. And that will mean years--perhaps decades--of accurate measurements and trouble-free use.

DIAL INDICATORS VS. TEST INDICATORS

Test indicators are pretty distinct from dial indicators. The immediately obvious difference is that test indicators have lever-type contacts, while dial indicators have plunger-type contacts. Test indicators are also smaller and lighter than dial indicators. In general, the two tools are used in different applications, although there are areas of overlap, where either tool can do the job.

Dial indicators excel at repetitive, comparative measurements: when mounted in a fixture gage, the dial indicator's straight, vertical motion ensures that the contact always lands in the same place, relative to the fixture. This means that the indicator must be oriented vertically to the feature being measured, but for rapid quality inspection of part dimensions, a fixture gage equipped with a dial indicator is unbeatable in most circumstances.

Test indicators excel at consistency measurements, as opposed to comparative ones. They are used most often to explore relatively broad part surfaces in either one or two dimensions -- for example, measuring variations in height, flatness, or roundness. Test indicators are often used in combination with a height stand and a surface plate, and either the workpiece or the stand can be moved around freely on the plate. When combined with a V-block or a pair of centers, test indicators can be used to test for roundness or runout on cylindrical parts. The angular motion of the test indicator's lever allows the contact to ride easily over irregularities on part surfaces. This capability is lacking in dial indicators, because the vertical-action plunger may resist responding to surface irregularities pushing "sideways" against the contact.

This ability to ride over irregular surfaces also makes test indicators well suited for use in machine setups, particularly on lathes. The indicator is held by an articulated test stand, usually mounted right on the machine. The operator brings the indicator into rough contact with the chucked blank, then turns the spindle to obtain a very quick reading on runout. No mastering is required when checking roundness, runout, or flatness. You simply bring the indicator close to the part surface, push down on the lever to make contact with the part, and rotate the indicator's bezel to zero. It's far quicker than the typical setup for a dial indicator.

Test indicators can be oriented more flexibly relative to the workpiece than dial indicators, at a wide range of approach angles. The narrow lever and very small contact ball also fit readily into many places that dial indicators cannot reach, except with special attachments. On the other hand, test indicators cannot measure the depth of holes as dial indicators can. Neither are they well suited for use in most fixture gaging applications, nor in ID and OD gages, bore gages, thickness and height gages. These are all standard, no-questions-asked applications for dial indicators.

Spring force is much lower on test indicators, which may be desirable when measuring deformable materials. Test indicators are smaller and lighter than dial indicators, and these factors may be an issue in some fixtures. The dial itself on a test indicator is small, compared to those on dial indicators, so visibility is not as good. As with dial indicators, however, custom dial faces are available for test indicators for special applications.

Test indicators have generally higher resolution, but a shorter range of measurement, than dial indicators, although both factors overlap at the ends of the scales. Typical resolution (least grad) for test indicators is .0001" to .00005"; for dial indicators, it is .001" to .0001". Dial indicators usually have a total measurement range of at least .025", and .250" is also considered a standard figure, while long-travel units allow measurements out to several inches. The measurement range of test indicators is considerably shorter—usually between .008" and .030".

Test indicators are extremely useful little items that are sometimes overlooked in favor of the more familiar dial indicators. When choosing between the two, it's a matter of comparing their relative strengths and weaknesses in light of the requirements of the application.

DIAL VERSUS DIGITAL INDICATORS

When digital electronic indicators were introduced in the early 1980's, some observers expected them to become the indicator of choice. But in spite of electronic indicator's clear superiority for use in statistical process control and data collection systems, mechanical indicators retain other advantages and they are still frequently specified by many sophisticated users. Neither type is "better" than the other: the choice depends upon the application and the user's personal preference.

The clearest advantage of electronic indicators is in their use for data collection in process control. Electronic indicators can output measurements directly to printers or SPC programs with no operator errors in reading or recording. The operator only has to position the workpiece and press a button: he needn't even read the measurement. With dial indicators, the operator must interpret the pointer's position to read the measurement, then he must record it--generally by hand--and finally the data must be keyed into a computer. That makes three steps during which errors can and frequently do occur. In any situation, where data must be entered into a computer system, digital indicators are the only way to go. Of course, the user pays for this convenience: digital indicators usually cost significantly more than their mechanical counterparts.

Aside from the cost benefit, there is a great deal to be said for mechanical dial indicators. In many ways, the human brain is like an analog device, and it can often gather more information, more quickly, from an analog readout. When a measurement need only fall within a certain tolerance range, analog dials are often quicker and easier to read. An experienced gage operator can simply see whether the pointer is within tolerances without taking the time to actually read and interpret the numbers on the dial.

It is possible for QC inspectors to make consistently accurate go/no-go readings with dial indicators even before the pointer has stopped moving! They can tell at a glance approximately where the pointer will stop, and in many applications, that is close enough. Electronic indicators don't give you the option of approximating. When a digital device is flickering between six and seven, all of the elements in an LCD display may be lit, appearing as an eight. See accompanying illustration.

Skilled operators can "split grads" with dial indicators, i.e., resolve the pointer's position to an accuracy of about one-fifth of the gage's stated minimum graduation value. And analog dials enable the machinist to observe the direction his process is headed. If reading #1 measures 1/5 of a grad over zero, reading #2 is precisely zero, and reading #3 is 1/5 of a grad below zero, the user may be able to draw valuable conclusions about the condition of his tool. In other words, dials can provide more information than simply the dimensional measurement. a digital readout would read zero in all three cases, depriving the user of this additional information. On the other hand, for statistical process control purposes, it is necessary to eliminate all such interpretive data, which again recommends the digital solution.

A common, serious problem among users of dial indicators is the failure to notice when the pointer makes a full revolution or two. Parts that are grossly out of tolerance may appear to be within tolerances to an inattentive operator. In contrast, digital indicators never come “back to zero,” eliminating this problem entirely. Furthermore, all digital indicators can be made to signal out-of-tolerance dimensions.

Many electronic indicators have some form of supplemental analog display. These electronic emulation’s of analog performance serve to eliminate some of the cognitive disadvantages of digital displays and make electronic indicators “user-friendly.”

In spite of initial doubts, electronic indicators have proven to be highly reliable in the shop floor environment. Most have only a single moving part, so they may require less frequent cleaning than their mechanical cousins. With proper care, however, dial indicators last forever, and they never need batteries.

Finally, there are somewhat broader ranges of accessories for mechanical indicators, and they are more readily customized for special applications--the subject of next month’s column.

GAGING ID’S AND OD’S

Without a doubt, circles are the most frequently produced machined form, generated by many different processes, including turning, milling, centerless grinding, boring, reaming, drilling, etc. There is, accordingly, a wide variety of gages to measure inside and outside diameters. Selecting the best gage for the job requires a consideration of many variables, including the size of the part, the length or depth of the round feature, and whether you want to gage in-process or post-process.

ID/OD indicator gages come in two basic flavors: benchtop and portable, as shown in Figures 1 and 2. Benchtop gages are generally restricted to measuring parts or features not more than 1" deep or long, while portable ID/OD gages can go as deep as 5" or so. If you need to measure hole IDs deeper than that, bore gages or plug gages are the tool of choice. On the other hand, snap gages are commonly used for ODs on longer parts — shafts, for example.

Getting back to ID/OD gages, the choice between benchtop and portable styles depends mainly on the size of the part being measured, and whether the part will be brought to the gage, or vice versa. If the part is large or awkward to manipulate, or if it's set up on a machine and you want to measure it there, then a portable, beam-type gage is required. Beam-type gages are available with maximum capacities from 5" to about 5', the largest ones being used to measure bearings and castings for jet engines and similarly large precision parts. Range of capacity is typically about 6", while the measurement range is determined by the indicator installed.

Most portable ID/OD gages lack centralizing stops, so they must be "rocked" like a bore gage to find the true diameter. When rocking the gage, use the fixed contact as the pivot, and allow the sensitive contact to sweep across the part. Likewise, if the gage must bear its own weight against the part, make sure that weight is borne by the fixed contact, not the sensitive one.

A special fixture with sliding stops at major increments is used to master for large ID measurements. Gage blocks are inserted in the fixture to "build out" the desired dimension. For OD measurements, calibrated "end rods" are often used: there is nothing especially fancy about these rods — they're simply lengths of steel, carefully calibrated for length. When mastering and measuring at large dimensions, the gage, the master, and the part must all be at the same temperature. Otherwise, thermal influences will throw off the measurement.

Even so, don't expect very high precision when measuring dimensions of a foot or more. Most indicators on these large-capacity gages will have minimum grads of .0005". This is adequate, given the inability of most machine tools to hold tolerances much tighter than about .002" for parts that large. Beware the gage maker who tries to sell you a 3-foot capacity ID/OD gage with .0001" resolution: it's probably not capable of repeatable measurements.

Benchtop gages are used for smaller parts (diameters ranging from about .25" to about 9" maximum), and they're capable of higher precision. (.0001" is readily achievable.) There are two basic benchtop configurations: T-plates, and V-plates. A T-plate gage has sensitive and fixed contacts oriented normally, at 180_ from each other, to measure true diameters. An extra fixed contact, oriented at 90_ or 270_, serves to aid part staging. A V-plate gage has two fixed contacts offset symmetrically from the centerline, and the part is held against both of them. This arrangement requires a special-ratio indicator, because motion at the sensitive contact is actually measured relative to a chord between the fixed contacts, not to a true diameter.

This three-point arrangement is useful if the production process is likely to induce a three-lobed condition on the part — for example, if the part is machined in a three-jawed chuck. By rotating the part in a V-plate gage, one can obtain an accurate assessment of deviation from roundness. If the process is expected to generate an even number of lobes, then the T-plate layout is more appropriate to measure deviation.

Because they are self-centralizing, benchtop gages are capable of rapid throughput. To further accelerate gaging with either benchtop or portable gages, mechanical dial indicators can be replaced with electronic indicators. The dynamic measurement capabilities of the latest generation of digital indicators enable them to capture the minimum or maximum reading, or calculate the difference between those two figures. Operators are thus freed from having to carefully monitor the motion of a rapidly -swinging needle on a dial indicator when rocking a portable gage, or checking for deviation on a benchtop version.

ELECTRONIC

Mechanical gages are familiar and economical. Air gages offer non-contact measurement and ease of use. But for the highest levels of accuracy and performance, it's hard to beat electronic gaging. No other method combines all this: extremely high resolution; relatively long range; adjustable magnification; programmability; digital output; and flexibility to move from job to job.

The "basic" electronic gage consists of three elements: a gage head; an amplifier; and a fixture or a stand to position the gage head relative to the workpiece. We'll touch on each separately.

The most common gage head type is the LVDT (linear variable differential transducer), an electromechanical device consisting of a primary coil, flanked by two secondary coils connected in series, all surrounding a movable magnetic core (the spindle) which provides a path for magnetic flux linking the coils. When the primary coil is energized by a sinusoidal signal from the amplifier, voltage of opposite polarity is induced in the secondary coils. The device's net output is the difference between the voltages of the two secondary coils, so when the core is centered, net output is zero.

The null or zero position is very stable, making LVDTs ideal for high repeatability comparative measurements. And because the LVDT works on an inductive principle, its resolution is, in theory, virtually infinite. In practice, it is limited by the amplifier's ability to amplify and display the results. Ranges vary from ±0.010" to ±0.100" (±0.250mm to ±2.500mm), with linearity from 0.5% to 0.05% over the nominal range.

Even standard-duty LVDTs are very rugged, and heavy-duty versions are capable of extended use in the harshest environments. Less than 3" (75mm) long and about the diameter of a pencil, they can be laid out with great flexibility in fixture gages.

Gaging amplifiers are made in analog and digital versions. Analog amps are preferred where highest resolution is required (at short range); where multiple-range capability is desirable in a single task; where measurement involves watching trends (such as approach-to-size); or where part motion or exploration is required (e.g., measuring flatness over a large area). Digital amps are preferable where high resolution and relatively long range are required; where the measurement is static (no motion between part and gage); and where digital output is required for data collection or machine control. In general, analog amps tend to be used in machine setup and surface plate measurements, while digital amps are used in high-volume inspection applications.

Many amps have two input channels, and the ability to combine signals from two transducers into one measurement is another benefit of electronic gaging. In "differential" mode, the amplifier is programmed to add or (more commonly) subtract one signal from the other. This gives the gage the flexibility to measure parts when mechanical references are difficult or impossible to establish, or when two variables may exist simultaneously: for example, on nominally round parts that are subject to dimensional variation and out-of-roundness. Depending on gage setup, the amplifier can be programmed to display either or both variables.

A typical digital amplifier might offer a choice of three measurement range/resolution combinations: ±0.100"/0.0001"; ±0.010"/10 microinches; and ±0.001"/1 microinch (±2mm/0.001mm; ±0.200mm/0.0001mm; and ±0.020mm/0.00002mm). It is important to remember that microinch/sub-micron resolution on the display does not necessarily mean that level of accuracy in practice. The accuracy of the fixture and the master, the geometric consistency of the workpiece, the stability of the gaging environment, and other conditions will influence gaging results. In practice, accuracy below 10 microinches (0.000025mm) generally requires a laboratory environment.

In order to achieve the best accuracy under shop-floor conditions, it is essential that the gage head stand be as sturdy and stable as possible. Platen, post, arm, and mounting bracket must all be totally rigid when locked. For high-precision height gaging, the arm assembly is often equipped with a lead screw mechanism, because the extra-sturdy arm is too heavy to be conveniently raised or lowered manually.

Another great benefit of electronic gaging is the ease with which components can be swapped around for different jobs. An amplifier that is used with two LVDTs for differential measurements in a fixture gage today may be hooked up to a single lever-type gage head in a comparator stand for height gaging tomorrow. Likewise, a gage head may be used with analog amplifier one day, and with a digital amp the next. No matter what your dimensional gaging problem, an electronic gage can probably be configured to handle it without too much fuss.

ELECTRONIC AMPLIFIERS: MORE THAN JUST READOUT DEVICES

Electronic gaging amplifiers are one of those devices whose full potential is rarely appreciated by their owners -- sort of like Range Rovers that never leave the pavement. Gaging amplifiers are often used simply as replacements for dial indicators where a higher degree of resolution is required. This is to ignore numerous opportunities to make gaging more efficient and productive.

Some amplifiers, for example, incorporate dynamic measurement capabilities, including Minimum (Min.), Maximum (Max.), and Total Indicated Reading (TIR) functions. The amplifier "remembers" the highest and lowest points measured on a part, and displays either or both of them, or subtracts the Min. from the Max. to calculate TIR.

This is useful when gaging round parts in a V-block fixture, or measuring the height of a flat surface. The operator can quickly turn a shaft through a complete revolution, or move a flat part around under the gage head, without pausing to read the display. When manipulation of the workpiece is complete, the operator may select to display the maximum or minimum ID, OD, height, depth, or runout.

Other advanced functions can speed gaging setups. The "auto-zero" function is the electronic equivalent of the rotating bezel on mechanical dial indicators: the operator brings the gage head into rough contact with the master, and simply zeroes the amplifier, eliminating the need for ultra-careful positioning of the gage head. A "master deviation" function allows the addition of a fudge factor to the zero setting. Say your spec calls for a nominal dimension of 1.99980", but you've only got gage blocks handy for 2.00000". No problem. Simply set your zero at 2.00000", master the gage, program in a deviation of +.00020" to all measurements, and *voila*! Quick and easy mastering, without the hassle of post-measurement arithmetic.

A "preset value" allows switching between comparative and absolute measurements. In other words, instead of gaging deviation from nominal, the amplifier displays actual part dimensions. (In the above example, if a part is .00010 above nominal, the display will read 1.99990".)

Many amplifiers accept signals from two or more gages. This means that more than one part feature can be measured on a multi-gage fixture, by simply "toggling" between the inputs. Somewhat more sophisticated is the capability for differential measurements, in which the amplifier subtracts the reading of one gage head from the other: for example, you can derive straightness by calculating the difference in height of two co-linear points on a shaft.

Amplifiers also allow the user to establish tolerance limits, and some incorporate green, amber, and red lights to indicate "in tolerance," "approaching limits," and "out of tolerance" conditions. Alternately, the lights can indicate different part-size categories for match-gaging applications. Through digital output ports, the same electronics can be used to drive large accessory lights, enhancing parts sorting efficiency or bad-part identification in high-volume applications.

These digital output ports represent a great benefit of modern benchtop gaging amplifiers. Through them, gaging data can be used to control production machinery on an in-process basis, replacing expensive, dedicated closed-loop controllers at a fraction of the cost.

In one real, representative application, a gage head is positioned to measure a workpiece while it's still on a grinder. The user of this system assembled it using an off-the-shelf, hermetically sealed gage head, and a standard benchtop amplifier connected via the digital I/O ports to the grinder's computer-numeric controller. The grinder shifts to a shallower depth of cut when the gaged data approaches the specified dimension, and stops automatically when the spec is reached. As long as the system is calibrated adequately, no post-process gaging is required.

Besides these enhancements to the gaging process, the most important and widely used feature on modern amps is the RS-232 port for data collection. Now, through SPC, intelligent decisions can be made about the sample lot or the process. Amplifiers also provide analog output to drive strip chart recorders for continuous part measurement.

Not all gaging amplifiers incorporate all of the features listed here, although most modern amps incorporate some of them. When selecting a new amplifier, one can readily enough identify the product features needed to meet the requirements of the application. For those who are currently using amplifiers simply to take comparative measurements, it may be worthwhile to review the owner's manual, to look for built-in functions that can enhance your productivity.

ELECTRONIC HEIGHT GAGES

In past columns we've looked at "basic" comparative height gages, which are used for layout tasks and other surface plate measurements. These consist of a comparator stand, plus a test indicator or an electronic gage head and amplifier. Related to these are instruments known as Electronic Height Gages. These offer a high degree of flexibility and functionality, so that, in addition to lab-based work, they are useful as production gages. In quality departments, they are used for first part and incoming inspections, and layout work, while on the shop floor, machinists use them for checking features on one-off parts.

The key features of the electronic height gage are: a probe that senses when the part is touched; a glass or capacitance scale that tracks the probe's height; and a readout/control unit. Many also incorporate a motor drive to position the probe. There is a base and a body, to maintain the components in a stable, rigid relationship, and to accurately position the scale perpendicular to the surface plate on which the gage rests. And often, there is an internal pump that generates a thin cushion of air beneath the base, allowing the gage to be moved around easily on the surface plate.

Glass and capacitance scales have gotten so good that these gages are reliable enough for shop-floor use, and so accurate over a long range as to blur the lines between comparative and absolute gaging. Most height gages can measure in both modes, and even toggle between them on a single measurement. Resolution of .0001"/.001mm, with accuracy of .0005"/.013mm over a range of 24"/615mm is common, while high-end instruments offer resolution down to 10µ"/.5µm and accuracy of .00012"/.0025mm.

Two sensing technologies predominate: touch triggers and active probes. Both types can be set to trigger from both downward and upward touches. Once these points are collected, it's easy to calculate the difference between them, for either inside measurements (such as slot lengths and widths, and inside diameters) or outside measurements (such as ODs or thicknesses). One can also average the two readings to find hole centers or center lines. From there, it's an easy step to calculate distances between centers.

The more common touch triggers send a signal to the scale only once per touch. Active probes, found on higher-end systems, constantly update their position, and record the position once they reach a stable reading on the part. In addition to single-point measurements, gages with active probes can be used for "dynamic" measurements, to explore a feature for straightness, flatness, MIN, MAX, or TIR.

Active probes have the potential to generate more accurate diameter measurements, because the user can tram the gage perpendicularly to the feature's axis, to capture the highest and lowest points on the top and bottom surfaces. (See figure.) To correctly measure a diameter with a touch trigger, a special contact is used, which is designed to seek the low or high point of the diameter.

Even the relatively simple control units associated with touch triggers tend to be highly capable. These are usually programmable for multiple measurement routines, can accept presets, and calculate widths, thicknesses, and distances between centers.

More powerful controllers, which usually accompany active probes, are required for dynamic measurements. These data processors are capable of generating SPC reports, and turning the single-axis height gage into a virtual two-dimension measuring machine. One can measure bolt-hole patterns and similar 2D relationships, by measuring the height of the holes, then reorienting the part 90° and remeasuring the hole heights again. The controller includes a one-button "90° flip" function to calculate results as X-Y coordinates (e.g., a hole center is 6.000" in from one edge, and 2.000" from an adjacent edge) or as polar coordinates (e.g., a hole center is 16.342° from a reference point, on a hypotenuse of 4.500").

The gage must be zeroed before measuring parts. This is usually done by touching the probe to the reference surface—usually a surface plate**.** Gages can also be referenced against a gageblock, or against a datum on the workpiece itself.

Before measuring inside or outside dimensions, the diameter of the ball end of the probe must be compensated for. This involves touching the probe to the top and bottom of a special reference artifact. The controller calculates the diameter as the difference between the measured reading and the known distance between the two reference surfaces.

While general-purpose measurement devices like electronic height gages can't compete with some types of comparative gaging for measurements requiring very high resolutions or throughput, they are ideal for most surface plate layout work, and for inspection of parts produced in small quantities.

AIR

It is perfectly natural that machinists should have an affinity for mechanical gages. To a machinist, the working of a mechanical gage is both straightforward and pleasing. Air gages, on the other hand, rely on the action of a fluid material, the dynamics of which are hard to (shall we say?) grasp. But air gaging has many advantages over mechanical gages and should be seriously considered as an option for many applications.

Air gages are capable of measuring to tighter tolerances than mechanical gages. The decision break-point generally falls around 0.0005 inch; if your tolerances are tighter than that, air gaging provides the higher resolution you will need. At their very best, mechanical gages are capable of measuring down to 50 millionths, but that requires extreme care. Air gages handle 50 millionths with ease, and some will measure to a resolution of 5 millionths.

But let's say your tolerances are around 0.0001 inch and mechanical gaging would suffice. Air still provides several advantages.

The high-pressure jet of air automatically cleans the surface of the workpiece of most coolants, chips, and grit, aiding in accuracy and saving the operator the trouble of cleaning the part. The air jet also provides self-cleaning action for the gage plug itself. However, the mechanical plug-type gages can become clogged with cutting oil or coolant and may require occasional disassembly for cleaning.

The contacts and the internal workings of mechanical plug gages are subject to wear. There's nothing to wear on an air plug except the plug itself, and that has such a large surface area that wear occurs very, very slowly. Air gages consequently require less frequent mastering and, in abrasive applications, less frequent repair or replacement.

On some highly polished or lapped workpieces, mechanical gage contacts can leave visible marks. Air gaging, as a non-contact operation, won't mark fine surfaces. For the same reason, air gaging can be more appropriate for use on workpieces that are extremely thin-walled, made of soft materials, or otherwise delicate. Continuous processes, as in the production of any kind of sheet stock, rolled or extruded shapes, also benefit from non-contact gaging.

Air equipment can save time in almost any gaging task that is not entirely straight-forward. Air plugs with separate circuits can take several measurements simultaneously on a single workpiece, for example, to measure diameters at the top and bottom of a bore for absolute dimensions, or to check for taper. Jets can be placed very close together for measurements of closely spaced features.

Air plugs are available (or can be readily engineered as “specials”) to measure a wide range of shapes that would be difficult with mechanical tools. Examples include: spherical surfaces, interrupted bores, tapered bores, and slots with rectangular or other profile shapes.

It would be possible to design a fixture gage with a number of dial indicators to measure several dimensions in a single setup, such as diameters of all the bearing journals on a crankshaft. But a fixture gage using air gaging will almost inevitably be simpler in design and fabrication, easier to use, less expensive and more accurate.

Because of the relative simplicity of fixture design, air gaging is especially suited to relational, as opposed to dimensional, measurements, such as squareness (see illustration), taper, twist, parallelism, and concentricity.

Air gaging isn’t perfect, though. Its high level of resolution makes air gaging impractical for use on workpieces with surface finish rougher than 50 microinches Ra because the readings would average the highs and lows of the rough surface. Most important, air gaging has relatively high initial cost, so it is usually reserved for large production runs. Clean, compressed air is also expensive to generate and must be figured into the equation.

In general, however, air gaging is the fast, economic choice for measuring large production runs and/or tight tolerances.

AIR GAGING FLEXIBILITY

In a previous columns, I touched on several applications where air gaging is particularly practical. These include relational, as opposed to dimensional, measurements, such as distance between centers, taper and concentricity. Along with high resolution and magnification, speed and repeatability, air gaging exhibits great flexibility.

Air gages are often simpler and cheaper to engineer than mechanical gages. They don’t require linkages to transfer mechanical motion, so the “contacts” (jets) can be spaced very closely, and at virtually any angle. This allows air to handle tasks that would be difficult or extremely expensive with mechanical gaging.

Gaging the straightness and/or taper of a bore is a basic application that benefits from close jet spacing (see Figure 1). All it takes is a single tool with jets at opposite sides of the gage’s diaphragm. The gage registers only the difference in pressure between the two sets of jets, directly indicating the amount of taper.

The concept can be applied to a fixture gage, to measure several diameters and tapers in a single operation. This fixture would be much simpler than a comparable gage equipped with mechanical indicators, each one outfitted, perhaps, with a motion transfer linkage and retracting mechanism. And the air gage could have an electrical interface to single in- or out-of-tolerance conditions with lights--much quicker to read than dial indicators. From one basic concept, we have just described at least four options (there are more). How is that for flexibility?

Note the basic principle: air circuits operating on one side of a diaphragm measure dimensions; circuits on opposing sides measure relational measurements or differences between features. The beauty of the concept is that you can choose to ignore dimensions while seeing only relational measurements, and vice versa. You never have to add, subtract, or otherwise manipulate gage data. It can all be done with direct-reading.

Consider, for example, the fixture gate which allows the shaft to be rotated. Two jets on opposing sides of the journal, acting on the same side of the diaphragm, will accurately measure the diameter of the journal, even if it is eccentric to the shaft. As the shaft is rotated, the air pressure increases at one jet, but decreases at the other one. Total pressure against that side of the diaphragm remains constant, so we obtain a diameter reading.

If the two circuits operate on opposite sides of the diaphragm (see Figure 2), the gage reflects not the total pressure of the circuits, but the difference between them. Higher pressure on one side or the other, therefore, indicates the journal’s displacement from the shaft centerline.

Naturally, one can position the jets and circuits to measure both features at once, and add another set to check for taper. Could you design a mechanical gate to accomplish all this at once? Perhaps, but at the cost of mechanical complexity.

The same principles apply to gages designed to measure the squareness of a bore (see my July, 1992, column). The included angle of a tapered hole, or the parallelism (bend and twist) and distance between centers of two bores (such as, a connecting rod’s crank and pin bores). Bore gages with the proper arrangement of jets can turn checking barrel shape, bellmouth, ovality, taper and curvature into quick, one-step operations.

Contact-type air probes, which use air to measure the movement of a precision spindle, provide the major benefits of air gaging (high resolution and magnification) where the use of open air jets is impracticable for use in measuring.

Open jest can’t measure against a point or a very narrow edge. The narrowest jet orifices are 0.025 inch, and these require a somewhat broader workpiece surface to generate the necessary air “curtain” to read accurately. Contact-type air probes, however, can gage with point or edge contact. Rough surfaces (above 50 microinches Ra) will baffle an open jet, but present no problems to a contact probe. And where open jets are limited in range to 0.003 inch to 0.006 inch measuring range, contact probes can go out to 0.030 inch (at some loss in sensitivity, however). Contact probes are often mounted in surface plates to measure flatness. Depth measurement of blind holes is another common use for long-range probes.

You needn't be a gage engineer to appreciate the flexibility of air gaging, or to understand how it can simplify gaging tasks. Just remember that virtually all kinds of measurements -- both dimensional and relational--can be performed with air, and that the more complex the task, the more air recommends itself.

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AIR GAGE – CHOOSING THE RIGHT ONE

Air gaging has many advantages as an inspection method. It is quick and easy to use, requiring little skill on the part of the operator. It is highly adaptable to measuring special features for both dimensional and geometric tolerances, ranging from simple IDs and ODs to taper, flatness, and runout. With different tooling readily installed on the gage display unit, it can be highly economical. And as a non-contact form of measurement (in the sense that there are no hard contacts), air gaging is useful for measuring delicate or flexible surfaces, and for monitoring the stability of continuous processes such as drawing and extruding.

Once the decision has been made to use air, the user can choose between three basic types of gages, each operating on a different principle. These are: the flow system; the differential pressure or balanced system; and the back-pressure system.

In older flow-type gages, air flows upward through a graduated glass column containing a float. Exiting the column, it flows through a tube to the tooling, where it exits through precision orifices or jets. Flow increases with clearance between the jets and the workpiece. When clearance is large, air flows freely through the column and the float rises. When clearance is small, air flow decreases and the float descends. Flow systems are not very popular in production environments, because they do not readily provide high magnification, and tend to be sensitive to clogging.

The other types of air gages measure pressure, not flow. As clearance between the jets and the workpiece increases, pressure decreases. In the back-pressure system, both the pressure meter itself and the bleed (i.e., zeroing circuit) are "Tee'd" off of a single air line—at the end of which is the tooling. Back-pressure systems are often called "dual master" systems: with a relatively short range of linearity, two masters are required to set the upper and lower tolerance limits.

In the differential system, the line is split into two legs. The bleed is at the end of one leg; the tooling is at the end of the other; and the bellows-type meter is located between the two legs. When pressure in both legs is equal, the meter is centered at zero. When a change in distance between the tooling and the workpiece causes pressure in the measuring leg to increase or decrease, the bellows reacts accordingly, and this is reflected on the meter. Differential systems offer linear response over a relatively long range: a single master is therefore sufficient to establish the zero point and still assure excellent accuracy on both the plus and minus sides.

Both differential and back-pressure systems are very well suited to production gaging applications, for different reasons. Differential systems are capable of higher magnification and discrimination; are easier to use because of greater tool-to-part clearance and the requirement for only one master; and are more stable. Back-pressure systems offer lower cost, adjustable magnification, and greater interchangeability of tooling between manufacturers. See the table for a summary of benefits associated with these gages.

BACK-PRESSURE VS. DIFFERENTIAL AIR GAGING

Back Pressure (Dual Master) Gages

- *Adjustable magnification; tooling flexibility.*
- *Less costly tooling.*
- *Higher air pressure: cleans part surface more*
- *effectively.*
- *Two masters provide greater traceability.*
- *More manufacturers; wide compatibility.*

Differential (Single Master) Gages

- *Higher magnification, discrimination; longer range.*
- *Greater tool-to-part clearance reduces wear, speeds usage.*
- *Better stability, dependability; no drift. Better for automatic control applications, and data collection for SPC.*

Single master makes gage easier, quicker to set.

SURFACE

When an engineer includes a surface finish spec on a print, the intent is usually not just to make the part look good. Surface finish affects how a part will fit, wear, reflect light, transmit heat, distribute lubrication and accept coatings. The finish should be determined by the part's function: you want a surface that fulfills the engineering requirements of the application, without wasting time and effort on a higher quality finish than is necessary. (In fact, many applications do better with a certain amount of "texture," and too fine a finish can be as bad as too coarse.)

Thirty years ago, when most dimensional tolerances were measured in thousandths of an inch, the difference of a few millionths in surface finish was often irrelevant. Now that tolerances of "tenths" or even tens of millionths are commonplace, variations in surface finish represent a sizable percentage of the total error budget. Note the following example:

The maximum peak-to-valley height on a surface is usually four or five times greater than the average surface finish, as measured by the R_a method. A part with an R_a value of 16µ", therefore, probably has a peak-to-valley height of 64 µ" or greater. If you're trying to meet a dimensional spec of .0001", the 16µ" finish represents over half the allowable tolerance.

As shown in Figure 1, surface finish -- also known as profile -- is composed of two components: waviness and roughness. Waviness, or longer-wavelength variation, is caused by macro-type influences, like worn spindle bearings, or vibration from other equipment on the shop floor. Roughness -- the short-wavelength pattern of tool marks from grinding, milling or other machining processes -- is influenced by the condition and quality of the tooling. Both can be influenced by the operator's choice of feed rate and depth of cut.

Although fingernail scratch-pads may provide a usable guide to finish, they can't meet the modern requirements of documentation and traceability. Hence the increasing importance of surface finish gages. As shown in Figure 2, there are two basic varieties: skid-type, or averaging systems, and skidless, or profiling systems. Skid gages have a hinged probe assembly, with the probe riding next to a relatively broad skid that also contacts the workpiece. The skid tends to filter out waviness, so the probe measures only short-wavelength variations. A skid gage has a dial or LCD readout to display the measurement as a single numerical value.

Skidless gages incorporate a smooth, flat internal surface as a reference, so the probe can respond to waviness as well as roughness. In order to allow separate analysis of long- and short-wavelength variations, profiling gages usually generate a chart (on paper or on a computer screen) rather than a single numerical result.

Every application reacts differently to different combinations of roughness and waviness, and industry has responded by creating more than 100 different formulae with which to calculate surface finish parameters from the same measurement data. Many of these are very application-specific, and most shops are able to confine their measurements to a half-dozen parameters or so. In almost all cases, measurements are presented in microinch or micron units.

R_a is the most widely used parameter, because it provides an arithmetic average of surface irregularities measured from a mean line that lies somewhere between the highest and lowest points on a given cut-off length. A slightly more sophisticated variant, R_q, uses a root mean square calculation to find geometric average roughness -- an averaged average, if you will. Both of these, however, tend to minimize the influence of surface anomalies like burrs or scratches. If such factors are critical to the application, R_{max}, R_y, R_t, and R_{tm} all calculate roughness as a function of maximum peak-to-valley height. Also useful is R_z -- the "ten-point height" parameter -- which calculates the average of ten maximum peak-to-valley differences within the sampling range.

If surface finish is called out on a drawing but not otherwise specified, it is standard practice to assume R_a. But no single parameter is best for all types of parts, and many applications are best served by using two or more parameters: for example, R_a (average roughness) in combination with R_{max} (maximum roughness) may provide a good general idea of the part's performance, and alert QA to the presence of potentially damaging surface anomalies.

Surface finish is not simply a challenge to meet: it represents an opportunity as well. In some cases, if you can maintain good control over surface finish, you may be able to safely reduce precision in other areas. We'll look at the subject again soon.

SURFACE CONT.

R_a, or average roughness, is the most commonly specified parameter for surface finish measurements. Because it describes the arithmetic average deviation of a surface from a mean line, R_a provides a good general guide for part performance over a wide range of applications. But, as can be expected of anything intended for general-purpose use, R_a has numerous limitations when applications are highly specific, or when small details of surface finish can make a big difference in part performance.

The key to specifying and using R_a measurements successfully is understanding how average roughness relates to surface finish in general, and the relationship between the machining process and the profile.

As shown in Figure 1, surfaces with different profiles can have the same R_a value, and these differences might be critical in certain applications. The surface shown in the middle trace, if used in a relative-motion application such as a rotating shaft, might score bearing surfaces and cause bearing failure. A part with scratches in its surface, as illustrated in the bottom trace, might fracture prematurely under sheer stress. Clearly, different roughness parameters are required to ensure that the finish is appropriate to the application. In the above examples, the R_p parameter (peak height) could be used to indicate and guard against the condition in the middle trace. To determine maximum scratch depth, as in the bottom trace, one could subtract the R_p value from the R_y (maximum peak to valley height) value.

Engineers and quality organizations who do not understand roughness measurements sometimes specify extremely tight R_a values in an attempt to guard against occasional scratches or peaks. This is an uneconomic approach to quality. We have seen one ball manufacturer who was able to substantially undercut the competition for an aerospace bearing contract by showing the end-user how a looser R_a spec, in combination with control over the R_p parameter, could produce bearing life equal to that achieved with the existing, tighter R_a spec without control over peak height. The ball manufacturer understood that it was the peaks on the balls, not their average roughness, that were principally responsible for scoring the races, and he found it much cheaper to knock the peaks off than to meet the high-tolerance R_a spec that had been put in place.

Different machining processes naturally generate different tool patterns. The roughness produced by grinding, for example, is generally of a shorter wavelength than that left by turning. Milling leaves even longer wavelength patterns, though not as long as those produced by single-point boring. (Note that the wavelength we're referring to here is the spacing of the individual tool marks, not the waviness component of surface profile.)

When performing an R_a measurement, it is essential to choose a cutoff length appropriate to the process. The cutoff length should be short enough so that the measurement will not be influenced by waviness. On the other hand, it must not be so short that only a portion of a tool mark is measured, as shown in Figure 2. A cutoff long enough to include five complete sets of tool marks is desirable to obtain a good average roughness measurement.

Surface finish gages of the simplest type, that only measure R_a, aren't much help in determining whether you've got a peak-and-valley problem, or what the proper cutoff length should be. It may be necessary to perform a complete surface finish analysis, including a look at the waviness component, to get a full understanding of the profile. With that in hand, however, straightforward R_a measurements may be all you need to maintain control over your process.

SURFACE CONT.

The R_a parameter is the most commonly used measurement for surface roughness. Until recently, in fact, it was the only parameter recognized by ANSI, although new ANSI and ISO standards include many different parameters from which to choose. And while these additional parameters are useful in many applications to ensure or enhance functionality, R_a is still included in most specs as a good starting point and a basic benchmark of process consistency.

R_a can be measured with two types of contact gages, which are distinguished from one another by the nature of the probe or contact that traverses over the part's surface. In "skidded" gages, the sensitive, diamond-tipped contact or stylus is contained within a probe, which has a metal skid that rests on the workpiece. Thus, skidded gages use the workpiece itself as the reference surface. This is a relatively simple, inexpensive approach to surface measurement. Skidded gages sell for as little as $1,600, and some are small enough to fit into a shirt pocket.

Skidless gages use an internal precision surface as a reference. This enables skidless gages to be used for measurements of waviness and form parameters, in addition to roughness. The drive unit is larger and more complex, and a computer is required to handle the complex algorithms for numerous parameters. Skidless gages are indispensable for complex surface analysis but, at a cost of ten to twenty times that of skidded systems, they are impractical if R_a is the only parameter required.

Getting back to skidded gages, it is important to look at the design of the skid itself. Some probes have a simple button-like skid, which may be located either in front of, or behind, the stylus. Others have a donut-shaped skid, with the stylus extending through the hole in the middle. In most applications, both types perform equally well, but occasionally, one or the other might be required to obtain accurate results.

Under high magnification, some workpieces appear to have wavy surfaces of very short wavelength; this is especially so of EDM parts. While the inclination may be to measure these surfaces using a waviness parameter, the pattern is really a tool mark, so a roughness parameter like R_a is required. Surfaces of this type may cause problems for gages with button-type skids. As shown in diagram "A," if the distance between the skid and the contact is roughly half the wavelength of the surface waviness, then the skid and contact will trade places at the tops and bottoms of the waves as the probe traverses the surface. This has the effect of nearly doubling the vertical travel of the contact relative to the reference, which will produce results that may be unreliable or non-repeatable.

The donut-type skid avoids this problem, because it remains at or near the tops of the waves as it traverses, as shown in diagram "B." Thus, the contact's vertical travel is measured against a far more constant reference height.

But because probes with donut-type skids require substantial structure ahead of the stylus, they cannot reach certain features, such as surfaces next to shoulders. Probes with button skids mounted behind the stylus require little or no leading structure, and thus have the advantage of increased access. Special probes with button skids are even available to reach into groove bottoms several millimeters deep.

Some pocket-type roughness gages offer users the ability to switch probes. This can extend the capabilities of the gage, allowing the user to select a probe with a donut skid for use on short-wavelength EDM'd surfaces, and a trailing-button skid for use where access is restricted.

FORM

What do you do when you're doing everything right and it's still coming out all wrong? We had a case like this not too long ago, where a shop was making a spindle and bore assembly for a high precision application. The owner complained that while he was machining well within his specified -.0002 tolerance on the shaft, his parts were either causing excessive bearing loads, or worse, not fitting in the bores at all. "How can they be wrong," he said, "when everything measures right?"

What this fellow didn't realize was that there are more things which can go wrong with a part than dimension. Just as we cannot make parts perfectly to size, neither can we make them perfectly round or perfectly smooth. And, as we all move towards tighter and tighter tolerance machining, irregularities in shape and finish will have a greater and greater affect on our ability to make parts. This means we're all going to have to understand more about geometry and surface finish.

In the example above, analysis in our lab showed a consistent three-lobed out-of-round condition on the spindles which was making their effective diameters too large. Three-lobed out-of-round is very common when using centerless grinding, but it wasn't noticed in this case because: 1) the specs didn't call for any geometric analysis on the parts; and 2) the shop was only using a two-point dimensional gage which was incapable of detecting the problem.

Figure 1 illustrates the relationship between out-of-roundness and effective diameter on a three-lobed part. As you can see, any two-point measurement will yield a consistent diameter, because each lobe is geometrically opposed by a flat area. This measured dimension would fall somewhere between the inner and outer dotted circles. However, the effective diameter, or the amount of space this part would actually require to clear, would be the outer dotted circle, which encompasses all the lobes. In this case, because the tolerance was so tight to begin with, the increase in effective diameter caused by the roundness problem exceeded his total tolerance for the part.

So did that mean he had to invest in a lot of fancy lab equipment, or buy a new centerless grinder? Fortunately not. As noted, out-of-round conditions with an odd number of lobes are common with centerless grinding (the greater the number of lobes, the more closely you approach true round), and once understood, are easily compensated for. In this case, a simple V-block fixture was set up with the blocks at 60° to measure the effective diameter, and the grinder set accordingly. Without going through the math involved, other odd-lobed out-of-round conditions can be similarly detected, using V-block fixtures set at other angles (108° for five lobes; 138_ 40' for seven lobes; and so on).

Unfortunately, in this case (but not for this column!) out-of-roundness was not the only problem. There was also a problem with surface finish which, while specified, was not really being measured. The specs called for an average roughness (R_a) of no more than 4 μin., but when measured, the parts showed an R_a of between 15 μin. and 25 μin. Since the affect of roughness on overall tolerance is a factor of at least 8, and sometimes as much as 20 (see Fig. 2), the 25 μin. of roughness took up the entire .0002" tolerance range on these parts!

Again, the solution was not costly equipment -- surface finish gages are readily and economically available for shop floor use -- but an awareness of the problem and an understanding of the basic causes. A simple redressing of the wheel solved the problem here, and allowed our shopowner to resume his normal sleeping pattern at night.

But the lesson is an important one. A recent report by the National Center for the Manufacturing Sciences showed that machining tolerances have decreased by a factor of five within the last decade, and that even tighter tolerances are on the horizon. This means that things like geometry and surface finish are going to play an increasingly important role in machining operations. And we need to understand that role, if we are to continue to produce good parts. That's the shape of things to come.

FORM CONT.

Previously, we looked at the measurement of out-of-roundness. But roundness is far from the only circular geometry specification that machinists may be required to meet and, therefore, to inspect. Let's look at some of the other parameters. As we describe them, refer to the figure to see how each is indicated on part print callouts.

Roundness involves no datum: it is evaluated relative to the part profile itself, using one of the four methods discussed last month (Maximum Inscribed Circle, Minimum Circumscribed Circle, Least Squares Center, or Minimum Radial Separation). Eccentricity, in contrast, is measured relative to a datum, which is the center of part rotation, as established by the spindle of the geometry gage (or by a part feature defined as the datum that has been centered on the spindle). Eccentricity is the distance between the center of the reference circle used to calculate out-of-roundness, and the datum. As the part rotates 180° around the datum axis, the center of the reference circle is displaced by twice the eccentricity value: hence, concentricity is twice eccentricity. Both eccentricity and concentricity may be measured for features lying in a single plane, or in two planes.

Circular runout, another datum-referenced measurement, measures the radial separation of two concentric circles whose common center is the datum, and which entirely enclose the part profile. Circular runout is the result of the combination of two form-error factors: out-of-roundness, and out-of-concentricity. The two factors may be additive or may cancel each other out, depending on vector directions. Circular flatness (of a flange, for example) may be specified at an indicated radius, and measured in a circular trace. This is a datum-free measurement that uses either a minimum-zone or least-squares calculation, similar to those used in roundness measurements.

Circular flatness can be used as the basis for plane parallelism measurements. Care must be taken, however, in reading and interpreting callouts correctly. The statement "A is parallel to B" (within a specified tolerance) implies that surface B is the datum. Any out-of-flatness present in this surface is ignored, while out-of-flatness in surface A is included in the calculation. The gage user cannot treat the two surfaces interchangeably. If one excludes out-of-flatness of both surfaces, the measurement is defined as parallelism plane runout.

In order to measure a number of squareness-related parameters, a vertical datum axis must first be established by measuring the roundness of the part at two planes, thus creating a part axis between the centers of the two reference circles. After normalizing the part axis to the gage spindle's axis of rotation, the horizontal surface in question is gaged at a specified radius, and normalized to the datum axis. Perpendicularity includes the out-of-flatness of the horizontal surface, while perpendicularity plane runout ignores out-of-flatness. Squareness is defined as half the plane runout value—in other words, it measures only from the center of the part's rotation to the indicated radius, while perpendicularity plane runout measures the deviation across the entire circle.

All of the parameters above can be measured on so-called "roundness" gages, which do not provide a means for precision vertical movement of the gage head. "Cylindricity" gages, on the other hand, incorporate precision reference surfaces in the gage head positioning axes, permitting measurements of a number of additional parameters.

Cylindricity is a useful parameter that provides an overall assessment of part roundness, taper, and straightness. Because it is not possible to measure every point on a three-dimensional surface, part profiles are taken at a number of planes, then combined into a single cylindricity value. Statistical analysis, and experience, may be required to establish the number of sample profiles needed for an accurate measurement.

Cylindricity gages can also be used to measure the straightness of an ID or OD surface on a vertically oriented workpiece, by keeping the part stationary and traversing the gage head up or down. Straightness can then be used as the basis for linear parallelism measurements, comparing opposed ID or OD surfaces, or comparing an ID surface to an OD surface.

We haven't space here to describe additional, complex parameters such as coaxiality and total runout. The main point Alex wishes to make, however, is that numerous parameters have been developed in order to control the functionality of parts across a wide range of possible configurations and applications. Make no assumptions when gaging part geometry: be sure you understand what the parameter means before you try to measure it. A couple of useful reference sources are: *Geo–Metrics II* by Lowell W. Foster (Addison Wesley Publishing); and the ANSI B89.3.1 standard for out-of-roundness measurement.

FORM CONT.

A major aerospace customer complained that the air-ring gage we sold him was inaccurate. How did he know, I asked. Because, he said, he checked the measurements against a coordinate measuring machine and a supermicrometer he had in the shop. The CMM and the supermike agreed with one another closely, while measurements on the air gage differed from them by as much as .0004", ergo...

"Send me a few samples," I told him. "and we'll check them in our lab, where results are good to one millionth. Then we'll know exactly what size they really are, and which gage is at fault."

The lab identified at least part of the problem even before they put them on a gage. "Where are the witness marks?" they wanted to know. "Where, exactly, were these parts measured?"

"What difference does it make?" asked the customer. "They're simple OD cylinders."

In fact, it makes a lot of difference. If a part is slightly out-of-round, then the measuring method you choose will influence your measurement. A CMM, for example, will tend to average out errors of geometry and waveform. A supermike might give you the min, the max, or somewhere in-between, depending upon precisely where the measurement is made. The performance of an air ring can also vary between min/max and average reading, depending upon the number of jets, the part's geometry and surface finish, and the position of the part in the gage. None of them are necessarily wrong.

In this particular case, all three gages were giving accurate readings, but each one was measuring different dimensions. In the lab, we found that the parts exhibited geometry errors of as much as .0003", in addition to a small amount of waveform error. By measuring at different locations on the parts, the manufacturer sometimes picked up on that variation, and sometimes missed it. Simply by measuring from a consistent datum, we brought the air gage readings to within 50 millionths of the other two gages.

Instead of asking "is it accurate?" we should be asking "is it appropriate?" Most gages are accurate as delivered from the manufacturer, but every gage embraces certain limitations and assumptions. When selecting a gage or a gaging method, it is essential to establish a clear objective: Do you want to account for, or ignore, variation due to geometry, waveform, and surface finish? Do want to know the maximum OD of a part, or the minimum OD, or the average OD?

The answer to these questions depends upon the application. As a hypothetical example, consider a spool valve assembly, in which the bore is a perfect cylinder, and the spool itself has a slight three-lobed condition. The overall (average) diameter of the spool may determine the efficiency of the valve, but its maximum diameter will determine whether the two parts can be assembled or not. It's up to the user to determine which is the critical measurement, and then select the measuring tool most appropriate to the task.

Many gages offer a certain degree of flexibility. For example, it may be possible to specify the arrangement of jets in an air ring to automatically give the min/max, or average reading. Likewise, it may be possible to program a CMM to account for geometry factors. But before you can do either, you have to know what you want to measure.

Not surprisingly, this situation is paralleled by the factor of surface finish. Air gages tend to average, or ignore, surface roughness -- up to a point. A supermike, measuring on the "peaks," will tend to maximize its effect, while a CMM will randomize peaks and valleys, generally giving an average. In the aerospace manufacturer's case, we found that surface finish accounted for the remaining difference in readings between the gages.

And if that isn't complicated enough, here are two more factors you might want to consider: 1) The geometry of the gage's sensitive contact and holding fixture may affect measurements. 2) Masters are also machined parts that are subject to the influences of geometry and surface finish.

Why didn't we worry about this stuff before? Because even as recently as 10 years ago, tolerances were generally looser. But as tolerances get tighter, variations in part geometry and surface finish exert proportionally more influence on our measurements.

CMM AND NON CONTACT MEASUREMENT

IN PROCESS MEASUREMENT

GAGE PERFORMANCE

CALIBRATING FOR QUALITY

Just after our recent column on SPC appeared, George Schuetz came into my office waving a copy. “Excellent points,” he said. “But you glossed over a very big one.” “What’s that?” I asked, though I knew very well what he meant: George is our resident expert on calibration systems. “That you can’t make good parts with bad machines,” he said. “George,” I said, “this is a family oriented publication!” But he is right: just as you need to calibrate a gage in order to make accurate measurements, so a complete and ongoing program of machine calibration is a necessary prerequisite to any quality program.

George went on to say that calibration is often seen as too complicated and too time consuming to be worth the bother. And many shop owners reason, if the factory can’t set a machine right, how can they? So they continue to purchase machines without a thorough check of their full range of motion, they set them up and run them -- sometimes for years -- without recalibration, and then continually complain about their “inability to hold tolerance.” Well, says George, if this description makes your collar pinch, here are some things to think about:

First and foremost, set at the factory does not mean set in your shop. Too many things can happen during shipment and installation to even hope a new machine will be in spec without calibration. Second, once set does not mean always set. Strange things can and do happen to machine tools: an errant shaft of sunlight heating up a lead screw, or a minor lubrication problem in the ways, can throw a very expensive machine all out of position. You need to recheck that machine and its environment on a regular basis to ensure its ability to produce good parts. The good news, though, is that with the advanced equipment and software available today, calibration is not the bear it used to be. And most important, an ongoing calibration program in your shop can pay hefty dividends.

The most obvious of these is better quality parts. This means fewer rejects, reduced scrap, and less rework. But, says George, there are other, more subtle, benefits as well. One of these is in part and program editing. One of the “miracles” of the CNC revolution is supposedly the ability to program part routines and run them on different machines. This sounds good in theory, but in practice, it usually requires untold hours of programmer and operator time editing routines to accommodate machine peculiarities. Calibration minimizes this programming and editing time, so one tape really can serve several machines. This can make a major difference in the ability of a shop to respond in a JIT environment.

Another often overlooked benefit is the ability to document quality. This is valuable not only for vendor certification programs, but also as a marketing tool to help sell your capability. But the most important benefit of an ongoing calibration program is the increased understanding you gain about your machine's performance and your overall production environment. Calibration not only tells the good from the bad, it tells you how good your machines are, and how you can make them better, where they are best, and when you can expect them to give you trouble.

This knowledge can pay off in a number of ways. Scheduling, for example. Knowing in a very precise way what your machines are capable of will not only help you optimize production, it can also help you do things you didn't know you were capable of. Sometimes machines have "sweet spots," ranges in which they perform way beyond their stated accuracy specification. If you know where they are, you may be able to take very profitable advantage of them. Maintenanceand troubleshooting are another. Machines usually don't break overnight. There are warning signs. Monitoring performance on a regular basis can put you in the driver's seat. You will know when readjustments are necessary. You will be better able to schedule regular maintenance. And, you stand a better chance of being forewarned of major problems and avoiding the inevitable, middle-of-a-rush job breakdown.

Finally, regular calibration can help you determine when a favorite old machine has, shall we say, passed its peak. And when the time comes to replace it, the understanding you will have gained from ongoing calibration will make you a much wiser and better buyer. And help you prove it.

MASTERING FOR ID's and OD's

Once upon a time, an overly enthusiastic QC manager appealed to me, confused and dissatisfied. Here he was, spending good money to purchase very high quality masters, but his inspection process was no better than before. What was worse, his masters went out of calibration rapidly, pushing his costs even higher. The problem was that he was buying more accuracy than he could use.

Choosing the right tool for the job applies to mastering, just as it applies to every other area of gaging. While it may be possible to master a gage using a variety of standards, the best master for a job strikes a balance between accuracy, economy, durability, and ease of use.

Gage blocks are "primary standards," directly traceable to an "absolute" standard maintained by NIST, DIN, or ISO. Masters are "secondary" standards, because their sizes are established by reference to primary standards. While masters typically have a higher level of uncertainty than gage blocks, they are often the appropriate choice for production gaging. Gage blocks, after all, are square, while masters are typically round. If the parts being measured are round, and the gage is designed to measure round parts, the use of a round master will help avoid certain sources of geometry error.

A master ring or ring gage is basically a bore of a known dimension. The same device can often be used as a setting master for variable inside-diameter gages (such as bore gages, air tooling, and mechanical plug gages), for go/no-go mastering of fixed ID gages (such as a fixed plug gage), and for go/no-go OD inspection of male cylindrical workpieces.

Ring gages are made from steel, chromed steel for durability and corrosion resistance, or tungsten carbide for extreme wear resistance. They are classed by level of accuracy, with XXX indicating the tightest tolerances, XX, X, and Y being intermediate grades (in descending order), and Z being the lowest level of accuracy. Class tolerances vary by size: larger sizes have higher levels of uncertainty. Tolerances may be bilateral (i.e., evenly split between plus and minus around the nominal dimension), for use in setting variable gages, or unilateral for use as go/no-go gages. For rings, "go" is minus (-); for plugs, "go" is plus (+). Go/no-go gages may often be identified by a groove or ring on their knurled outside diameters.

Plug gages, for go/no-go measurements of part IDs, or for mastering ID gages, are also available in different materials and classes. Plug gages may be reversible or double ended, with a "go" end signified by a green stripe, and a "no go" end signified by a red stripe. Usually available only in sizes up to about 0.76", reversible plug gages can be disassembled to replace a worn end.

Plug gages are often identified by the names of their handle or mounting designs. Taper-lock plug gages usually range from 0.059" to 1.510", and have a handle on only one end. Tri-lock designs, also called discs, range from 1.510" to 8.010", and have handles on both ends of the mastering surface. Annular designs, for sizes from 8.010" to 12.010", are like wagon wheels, with handles for axles.

Specialty masters are available for a range of applications and odd shapes, including slots, splines, and tapers. Tool holder taper geometry is of increasing importance in precision machining, and manufacturers have begun to pay closer attention to taper quality. Taper plug gages can provide an indication of whether an ID taper is too steep or too shallow, or if the bore entry diameter is within tolerances. Inside and outside taper masters are also frequently used for setting taper air gaging. Such special-purpose masters make mastering and measuring quicker and easier, and usually cost more than standard gages.

In general, one should choose a master whose tolerance is 10 percent of the precision of the gage, while the gage's precision and repeatability should be 10% of the part tolerance. For example, if part tolerance is 0.001", gage precision should be 0.0001", and the master's tolerance should be 0.000010". It's usually not worthwhile to buy more accuracy than this "ten to one" rule: it costs more, it doesn't improve the accuracy of the gage, and the master will lose calibration faster. On the other hand, when manufacturing to extremely tight tolerances, a ratio of 4:1 or even 3:1 between gage and standard might have to be accepted.

Finally, here are some general guidelines for the care and feeding of masters: store them in a secure place; use a wax- or oil-based sealant to protect against corrosion; handle carefully—don't force or jam them onto the part; don't try to modify them; and when shipping for calibration, take steps to protect masters against damage and corrosion.

GAGING AND MASTERING UNCERTAINTY

When measuring parts to tolerances of a thousandth of an inch, we can usually be certain that our measurements are accurate to within a "tenth," as long as we follow standard gaging practice: i.e., master the gage frequently, maintain the gage in good working order, keep things clean, have the master recalibrated periodically, etc. But certainty becomes elusive at the microinch level. State-of-the-art machining practice is only just capable of producing gage standards and gage blocks to the required degrees of accuracy. However, their dimensions, as well as those of the workpieces, change readily with changes in temperature, the accumulation of infinitesimal amounts of dust, and minute variations in gaging practice.

Uncertainty can't be entirely eliminated, but manufacturers can successfully perform millionth measurements by relying upon relevant industry standards, which define how much uncertainty is permissible, and where. Particularly under ISO 9000, manufacturers must be able to document their use of reliable standards as the basis of their QA/QC efforts. But in all cases, uncertainty must be minimized, and one of the critical places to look for it is in mastering.

Gage blocks and masters have tolerances of dimension, surface roughness, and geometry: in other words, the masters themselves have inherent uncertainty. When gage blocks are wrung together, stacking error is introduced, combining all these sources of error with the added uncertainty that two or more wrings with the same blocks may produce different results. Gage blocks and masters are also subject to wear, which becomes significant rapidly at microinch tolerances.

Under the old "ten to one" rule, if you're measuring parts to 30 millionths, you want gage repeatability of 3 millionths, and a master that's good to 0.3 millionths. No one makes gage blocks to that level of accuracy, so we have to compromise and accept rules of five to one, or even less. That may be the best we can do.

Gage blocks are a "primary" standard: that is, they are documented and traceable back to an official, absolute standard -- in the US, to the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards). Documentation makes it possible to determine the level of accuracy in a given gage block.

Master rings and discs, in contrast, are generally considered to be secondary standards, because their size is established by reference to gage blocks. Traceability is thus one step further removed, which implies a greater level of uncertainty.

To document and minimize the level of uncertainty, gage blocks should ideally be sent to NIST for recertification. This way, you'll be mastering your gage at a single remove from the absolute standard: you can't get any closer than that. However, this may be impractical for a number of reasons, and commercial calibration houses may be able to provide faster service.

If you use a commercial service, it is important to choose one that sends its own primary blocks to NIST for calibration, to avoid adding unnecessary levels of uncertainty. Consider the following scenario:

You send your gage blocks to XYZ Accuracy Inc. But XYZ has its own blocks certified by ABC House o' Blocks. ABC sends its primary blocks to NIST for certification. Your blocks end up certified at three removes from NIST, with contributions of the following sources of uncertainty.

NIST uncertainty: 0.7μ"
ABC uncertainty: 1.5μ"
XYZ uncertainty: 1.5μ"
Total = 3.7μ"

While uncertainty isn't necessarily cumulative, it's easy to see how levels of uncertainty that may be insignificant for tolerances of .001" or .0001" can become critical when you're trying to measure to 10μ".

All this concern with mastering, calibration, and external standards is not an intellectual exercise of interest only to a chosen few: Any manufacturer hoping to meet microinch tolerances, obtain ISO 9000 certification, or satisfy many other industry standards, may be required to reference its measurement methods to officially recognized physical standards. Adequate traceability is an important issue, but one must be equally concerned with how many steps intervene between your own gage blocks and the official physical standard.

GR&R MEASURES MORE THAN JUST THE GAGE

A few weeks ago, a well-respected engine manufacturer approached me with a problem. He was unable to pass a Gage Repeatability and Reproducibility (GR&R) study. The odd thing was that he's been using the same gaging method successfully for over 40 years.

GR&R is a way to assess the reliability of your gaging results. A GR&R study involves taking a few gage operators, and having each of them measure a small number of parts, several times each. The results are compiled, and (after some mildly confusing arithmetic) reduced to a single number that indicates the total expected spread of measurements for a single part, for all trials, by all operators. The number is presented as a percentage: a GR&R of 30% means that all the results fall within a range equal to 30% of the allowable part tolerance. (This is slightly simplified, but close enough for our discussion.)

In the case of the engine manufacturer, his target was a 10% GR&R on a part with a total tolerance of .001" (±.0005"). In other words, all the measurements for a given workpiece should fall within a range of .0001".

The manufacturer was using a hand-held snap gage to measure the part. Mounted on the gage was a dial indicator with a resolution (i.e., grad size) of .0001". Everything seemed to be in order. He was following the old gage maker's rule of thumb that states that you should have a 10:1 ratio between part tolerance and gage accuracy. He had been successfully measuring the part for decades using the same type of gage. The part hadn't changed. The tolerance hadn't changed. And yet, he was achieving GR&R results of 30-35% -- not even close to the target.

He had failed to appreciate that something had indeed changed: his gaging requirement. Where previously a part would "pass" as long as it fell within a tolerance range .001" broad, GR&R now required that his gaging method meet a requirement much more demanding.

The problem wasn't his snap gage, which was in good condition, with a repeatability of 20 microinches. The problem was much simpler: he had the wrong dial indicator on the gage. With a resolution of .0001", the indicator itself ate up the entire allowance for variation under the GR&R study. And that left no room for the inevitable variation from other sources.

Remember the acronym "SWIPE"? There are five major factors that influence gaging results: Standard, Workpiece, Instrument, Personnel, and Environment. Each of these introduces a certain amount of variation to a measurement. Is the standard (the master) absolutely accurate? How about the workpiece's geometry? If it's out of round, it will generate different results every time you put it on the gage. The gage operators will introduce a certain amount of observational error, plus variability due to differences in gaging practice. Are you paying attention to the environmental factors that can influence a measurement: temperature, dirt, vibration, etc.? And, of course, there's the instrument -- the gage itself -- which could have stiction, wobbles, a misaligned holding fixture, or even, just possibly, a wrongly-specified dial indicator.

GR&R doesn't measure the gage in isolation: it measures the entire gaging process, with all of its influences and variables. If you want to achieve GR&R of 10%, then you'll have to be able to read the results to a considerably higher degree of resolution than 10% of the required tolerance. The old 10:1 rule is a general guide for a minimum level of accuracy -- not an inflexible dictum for every application.

We replaced the dial indicator on the gage with an electronic probe capable of resolving to 50 microinches. This tightened up the margin for error imposed by the gage, and allowed room for other variables. The manufacturer was then able to meet the 10% GR&R requirement -- without changing his manufacturing process, his gaging methods, or his gage.

If you fail a GR&R study, don't shoot the gage. You can't expect it to correct for errors from other sources. In fact, the moral of the story extends beyond the confines of GR&R. Any time you're assessing a gaging program or trying to determine your gage requirements, remember that the instrument is just one-fifth of the equation.

FUTURE TRENDS IN GAGING

GAGING TRENDS