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 <u>how</u> good your machines are, and how you can make them better, <u>where</u> they are best, and <u>when</u> 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.

CALIBRATING GAGES: YOUR PLACE OR MINE?

All gaging equipment must be calibrated periodically to ensure that it's capable of performing the job for which it's intended: i.e., measuring parts accurately. This has always been necessary for the purpose of maintaining quality, but there are now additional, external reasons to establish and maintain a regular program of gage calibration: customers' requirements. More and more OEMs demand that suppliers document their quality efforts from start to finish. ISO 9000 is one more manifestation of this trend, and it is forcing companies to examine their calibration programs, identify their weaknesses, and improve them wherever possible.

Some large companies with thousands of gages can cost-justify hiring or training specialists in gage calibration methods and supplying them with equipment and resources to perform virtually all calibration duties in-house. For most machine shops, however, the economical approach is to hire a calibration service.

ISO 9002, which applies to all manufacturing operations, requires suppliers to calibrate "all inspection, measuring and test equipment and devices that can affect product quality at prescribed intervals, or prior to use, against certified equipment having a known valid relationship to nationally recognized standards -- where no such standards exist, the basis used for calibration shall be documented." (ISO9002.4.10.b) Let's elaborate on some of these points:

"(P)rescribed intervals" usually translates into a minimum of once per year. Where annual calibration is inadequate to ensure accuracy, a shorter interval must be established.

"(C)ertified equipment having a known, valid relationship" means that the calibration house must have its own equipment certified. In the U.S., "nationally recognized standards" implies the National Institute of Standards and Testing (NIST), although other standards, such as DIN, may be used to satisfy overseas customers. "(W)here no such standards exist," usually refers to highly specific industries or products, where the manufacturer must develop his own standards and test methods -- (say, a foam pad of known density, used to master a chocolate-pudding-consistency gage). Calibration houses issue a certificate of calibration for every gage tested. These certificates, as shown in Figure 1, are essential for users to document their calibration programs. At minimum, they must include:

- The serial number and description of the gage tested.
- The serial number of the gage(s) used to perform the testing.
- The level of uncertainty of the calibration -- in other words, the tolerances of the data.
- A statement of traceability to NIST (or other standard).
- A serial number identifying the NIST test upon which the calibration house's own standard is based.
- Reference temperature under which the calibration was performed.
- Name of the customer; name and address of calibration service.
- Date of calibration and signature of the technician.
- Test results: i.e., error in the gage, measured at appropriate intervals across its entire range.
- If the gage is adjusted subsequent to testing, it must be recalibrated, with results as above.

Some providers automatically remind their clients which gages need to be calibrated, and when. Most gages can simply be boxed and shipped to the calibration house, although in the case of large, elaborate gages (e.g., circular geometry gages, CMMs) the mountain must come to Mohammed. The calibration service will come prepared with NIST-traceable gage blocks, precision balls, a thermometer, and any other standards needed to perform the job.

How can a machine shop without expertise in calibration intelligently select a provider? Naturally, cost and turnaround time are important, but don't sacrifice quality for convenience. Above all, ISO 9000 requires that consistent procedures be applied, and any professional calibration house should be able to document its methods in a procedures manual. Ask to see it, and if it's unavailable, look elsewhere.

Surprisingly, there are no certification standards for calibration labs themselves, so a supplier's reputation is important. Don't be afraid to ask questions -- lots of them. What are his areas of expertise? How are his technicians trained, and what is their level of experience? What test equipment is used, and to what standards can test methods be certified (e.g., MIL, GGG, ANSI)? What quality control methods are in place? What is the physical design of the facility, what are the control tolerances on temperature and humidity, and how is the equipment protected from the effects of outside vibration? Figure 2 shows an example of state-of-the-art isolation from dynamic forces: how does the facility under consideration compare? A visit may be well worthwhile.

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.

CONTROL THY GAGES

The number of gages and micrometers that are in use, but actually incapable of doing the jobs to which they are assigned, is alarming. Too many machine shops make assertions of accuracy for a part or a process, based on gages that are scratched, sticking, or in some other obvious or hidden way incapable of taking good measurements. And when asked to document that assertion, these shops rely upon a dog-eared certificate of calibration that's years old.

While it may be alarming, the fact that inaccurate gages remain in use is not surprising. After all, there's simply no such thing as a "perfect" gage: even the best-engineered and well-maintained instrument has some degree of uncertainty. Every time the gage is used, components are subjected to some infinitesimal amount of wear. At what point does inaccuracy cross the line between acceptable and unacceptable?

Depending on many variables of design and usage, some gages retain accuracy for years, while others require refurbishing every few months. Some may be chugging along just fine, when an accident puts them suddenly out of kilter. But eventually, every gage loses accuracy.

Gage control—a system of record-keeping used to track the use and condition of every gage in the shop—performs several important functions. By tracking when, where, and how each gage is used, it makes predictive maintenance possible, thus reducing scrap and rework. It's an important loss-prevention tool, helping to maintain your investment in valuable equipment. In the event that a number of bad parts slip through some level of quality control, it often permits analysis to determine how and when the problem occurred. Furthermore, it's essential to most relevant quality documentation programs, including ISO/QS-9000. (Although neither of these standards explicitly mentions how to control gages, it would be virtually impossible for a machine shop to demonstrate the required control over production without it.)

Although the gage control process is well defined by numerous company in-house and international standards, every shop must tailor the process somewhat to meet specific requirements. In large plants, it is often handled by the Inspection department, which may establish a dedicated staff, facilities for gage calibration and inspection, and a gage storage crib. In small shops, the responsibility may be assigned to production or materiel managers, or the chief inspector. In any case, those responsible usually maintain daily contact with Process Engineering and Production, to define gaging requirements, establish budgets, maintain inventory, and calculate depreciation and obsolescence.

As a starting point, every gage and instrument should be assigned a unique serial number. The numbering system may be very simple, or particular digits in the serial number may be designated to reveal specific information about the gage. The control record should also include the date of purchase, the name of the supplier, and a description of the gage type, including the manufacturer's model number. If the gage was custom-built, the record should reference the engineering file.

The record should also contain answers to these questions:

- Where is the gage right now?
- When, where, and to whom was it issued?
- How long has it been on the job?
- How is it being used; on what product, and how often?
- What was its condition when issued?
- When was it last calibrated? How accurate is it?
- When is it scheduled to be recalibrated?
- What is its GR&R on a particular process?
- Has uncertainty been established?

Manual record-keeping has largely given way to PC-based database software and specialized gage control programs, which have greatly increased the ease with which extensive records may be maintained and accessed. Among the many functions offered by commercially available programs, some automatically recall gages that are due for recalibration.

Historically, trade workers were often required to bring the tools needed to their jobs; this included machinists who were expected to provide their own gages. In many shops and plants, this practice still exists in modified form: the shop might provide gaging for inspection, but require machinists to provide gages for setups.

That practice is no longer viable. Manufacturers must be able to document procedures taken to assure quality. Unless 100 percent inspection is employed, this includes being able to demonstrate that setups were performed to a known degree of accuracy. This, in turn, requires gages whose accuracy is known. And that can only be done if the shop maintains control over all the gages in use.

A substantial investment is required to establish and maintain a gage control program. But through improved product quality, reduction of scrap and rework, loss prevention, tighter process control, and lower assembly costs, gage control almost always pays for itself over the long run.

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:

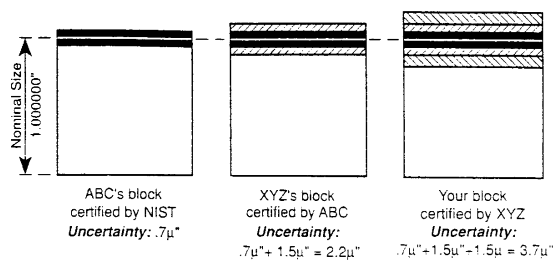
You send your gage blocks to XYZ Accuracy Inc. But XYZ has its own blocks certified by ABC House o' Blocks. ABC sends its primary blocks to NIST for certification. Your blocks end up certified at three removes from NIST, with contributions of the following sources of uncertainty.

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.

Fig. 1



UNCERTAIN ABOUT 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, and it thus involves more than just the gaging instrument. Gaging results are also influenced by the master, the part, the operator, and the environment. 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 (or Type A) errors, and systematic (or Type B) 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.

A few months ago we saw how a series of part inspection measurements will typically produce a range of results forming a bell-curve, in which the ±3 sigma limits comprise 99.97% of all readings. The same holds true for a series of repeated measurements on a single part with a single gage: due to random errors, the results will form a bell curve (although of course the range will be considerably smaller than for a production run).

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, of both A and B types, 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:

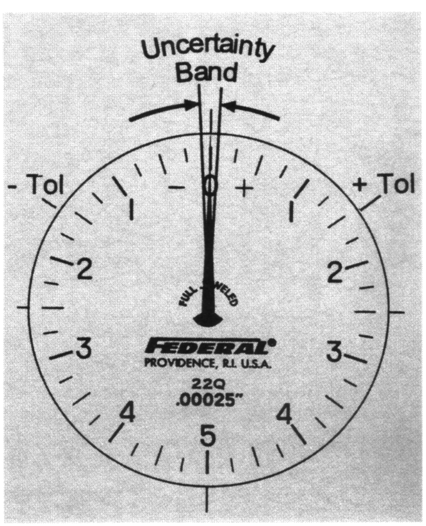
$$S_T = S_1 + S_2 + S_3 \ldots S_n$$

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 an educated guess, but 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.

When making a measurement, the range of uncertainty of the gaging operation which includes the master should be no more than a quarter of a graduation on an analog scale. Sometimes the range of uncertainty may not appear at all, but this does not mean that the error does not exist. Rather, it means that the indicating device does not have the discriminating ability to show it. Likewise with digital readouts: these errors may or may not appear, depending upon resolution.



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.

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.

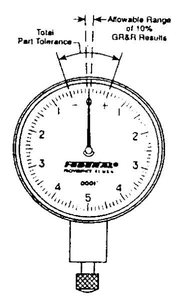
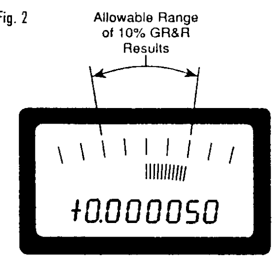


Fig. 2



The gage in Fig. 1 (left) could not pass a 10% GR&R study for a 0.001" part tolerance. Fig. 2 (above) shows one that could.

OPERATING CHARACTERISTICS AND CALIBRATION CURVES

Gage accuracy is described by a number of concepts, including repeatability, linearity, calibration, and "accuracy" itself. The Operating Characteristics (O.C.) curve presents an easy way to visualize what these terms mean, and how they are interrelated.

A simple non-magnifying measuring instrument, like a steel rule, produces an O.C. curve that is a straight 45° line. For any measurement (for example, at Point a), there is a 1:1 relationship between part size (horizontal axis), and movement along the instrument's scale or display (left axis).

Most gages employ magnification to make small changes in part size below .01" detectable on the display. For illustrative purposes, we'll use a very low magnification of 4:1, but in practice, most gages used in metalworking magnify distance by 100X, 1,000X or more.

The O.C. curve for a magnifying gage, such as an indicator height gage, is still straight, but it is steeper, indicating that the distance traveled by the tip of the indicator needle is greater than the change in part size. Point a' on O.C. Curve B shows the same size part that was measured on Curve A, but using a gage with 4:1 magnification (right axis).

The effect of instrument error is shown at Point e on Curve A, and magnified, at Point e' on Curve B. Because magnification enlarges mistakes, but does nothing to correct error, gage specifiers must be careful not to confuse high magnification with high accuracy.

Instrument error may be caused by improper use of the gage, or it may be inherent to the gage's design, the quality of its manufacture, or its condition. Examples of inherent errors include: incorrectly spaced graduations on the dial; imperfect gear profiles in dial indicators; improperly spaced lines on linear encoders or glass scales; and a master jet on an air gage that is partially clogged by dirt.

Annual gage calibration will uncover instrument errors. Where the cause of error is constant and the error repeats itself every time the gage is used, we speak of "calibration error," which can be plotted as a Calibration Curve. Using a calibration curve, an operator can manually apply correction factors to gage readings. Alternately, the indicator dial can be modified with uneven spacing between graduations, to correct for the error, while some electronic gages allow correction factors to be entered into memory, so that the readout displays the proper value.

WHAT'S WRONG WITH THIS PICTURE?

On the Care and Feeding of Master Rings and Other Metrology Artifacts

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. That's a 'no brainer'. 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.

WITH MASTER RINGS AND ENGAGEMENTS, SIZE MATTERS

A master ring, or ring gage, is basically a bore of known dimension. The precision hole is often 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, and for go/no-go OD inspection of male cylindrical work pieces. Ring gages are made from steel, chromed steel for durability and corrosion resistance, or tungsten carbide for extreme wear resistance.

They are often classed by level of accuracy, with XXX indicating the tightest tolerances; XX, X and Y being intermediate grades; and Z being the lowest. Class tolerances vary by size. Larger sizes have more open tolerances since they are harder to manufacture. Tolerances may be bilateral for use in setting variable gages, or unilateral for use as go/no-go gages. For rings, “go” is minus; for plugs, it’s plus. Go/no-go gages may often be identified by a groove or ring on their knurled outside diameters.

Example: for a 0.820” master ring the following tolerances would apply:

Class XXX=	0.00001”
Class XX=	0.00002”
Class X=	0.00004”
Class Y=	0.00007”
Class Z=	0.00010”

Of course, the better the class the more you have to pay. If you want to stay at a 5-star hotel or get the highest grade for your engagement ring, be ready to pay for it. It’s the same with master rings. The XXX ring is manufactured to a tighter tolerance, and there is cost involved with this. It may take longer to manufacture, take the skill of a higher paid technician, or if something goes wrong, it may have to be remanufactured and take longer to get.

Typically, the rule of thumb for selecting a master had been to choose one whose tolerance is 10 percent of the part tolerance. This, combined with the gage's performance, should provide adequate assurance of a good measurement process. It's usually not worthwhile to buy more accuracy than this "ten to one" rule: it costs more, it doesn't improve the accuracy, and the master will lose calibration faster. On the other hand, when manufacturing to extremely tight tolerances, one might need a ratio of 4:1 or even 3:1 between gage and standard simply because the master can not be manufactured and inspected using a 10:1 rule.

Take a taper master, for example. Say the angle tolerance is 0.001" over a 12-inch longer taper. Usually a gage or master is not made 12" long. Rather, it may be 1' long. At this length the same tolerance now becomes 83µ". Using the 10:1 rule, the master would have to be 8.3µ". Unfortunately, this gage would be virtually impossible to manufacture or even measure.

But there are alternatives that can allow these tolerances to be measured and can reduce the cost of your masters. Masters can be certified to their class (the XXX, XX, X etc.) or they can be certified to their size. What this means is that you may have the tolerance that requires a class XXX master ring. However, a suitable replacement might be a XX ring certified to size. What you will get with this ring is a Certificate that documents the ring's size at various locations and the calibration lab's measurement uncertainty.

Now you know that the ring met the XX class and you know the exact size of the ring. You can use this information to your benefit. When setting the gage to its reference (usually zero), set it to the actual master size. In effect, you are getting XXX performance from you XX ring. You've saved some money and probably sped up the delivery of your gage.

Wouldn't this be great if this worked for engagement diamonds also? That zirconium looks awfully good!