# GAGING THE "ODDBALL" APPLICATION

The gages and methods discussed in this column are usually of very general interest. Virtually all metalworking shops need to measure holes, thicknesses, and heights. Some shops, however, have to perform measurements that are more limited in application: some are industry- or even company-specific.

Oftentimes, manufacturers attempt to satisfy unusual gaging applications by designing and fabricating a gage in-house. Most of the concepts of gage design are straightforward, and clever machinists can figure out how to apply these concepts in fairly basic fashion, usually by incorporating stock components such as dial indicators and gage heads, into custom-made fixtures. Amateur gage design, however, may not be efficient. It's often more cost effective to let gaging experts work out the details and spread design costs over a larger number of users.

Following are examples of gages developed for specialized applications. There are two points to be made here: the first is that even the most obscure measurement tasks can usually be performed by relatively simple gages. The second is that many gage makers are more than willing to work on "oddball" applications, freeing gage users to concentrate on their real business.

There are hundreds of thousands of countersunk rivet holes in the skin of a typical airliner. To achieve maximum holding power and minimum wind resistance, the head of every rivet must sit flush with the outer surface of the skin. However, government standards strictly limit the degree to which a manufacturer can grind down proud-standing rivet heads. As countersink bits wear, countersink diameters and depths change. Riveters need to measure the countersinks, in order to pick the right size rivet from an available selection range.

Countersink gages, operate like hand-held, plunger-type depth gages, with special-ratio dials or electronics, to convert vertical movement at the contact into diametric measurements. The gage contact must be chosen to correspond with the included angle of the countersink. Some gages measure the major, or entry diameter, while others measure the depth of the minor diameter (where the countersink meets the straight hole). Although aerospace is currently the predominant application, other high-precision sheetmetal industries may soon follow suit.

More exotic is the Almen gage, which is used to measure and control the results of the shot peening process. Shot peening bombards a part with a stream of steel or glass particles, inducing sub-surface material compression and greatly reducing stress cracking under tensile loads. Shot peening is widely used on automotive and compressor crankshafts and conrods.

To measure the process, a thin metal test strip is subjected to the shot stream. The strip bends in a predictable manner, as a function of shot stream intensity. An Almen gage measures the radius of the strip. Gage manufacturers have developed innovative mastering strategies to take both the longitudinal and transverse curvatures of the strip into account, and use refined mechanisms and geometries to hold and measure the strip without distortion. Although the Almen gage is essentially a benchtop depth gage, it's these important details that make the gaging process quick and cost effective.

Aerosol and beverage can manufacturers have highly specialized gaging requirements. Tight tolerances must be maintained, both in order to ensure proper functioning of valves, seals, and pop-tops, and to save material: at production rates of several million units per day, a wall thickness variation of a few millionths quickly adds up to tons of aluminum. There are more than a dozen critical dimensions on most cans, including such arcane features as crimp groove location, valve stem height, and "tab top bubble height."

In order for SPC to be effective -- in order for gaging results to work their way back to the manufacturing process in a timely manner as the cans go whizzing by -- several dimensions must be measured very rapidly. Whole catalogs of can gages have been developed. At the lower end of the technology spectrum are specialized indicator gages, which differ from generic gages mainly in the shapes of their reference surfaces and sensitive contacts. Once again, the dimensions being measured here are simply variations on the basic themes of height, depth, thickness, ID, and OD. But the theme can be elaborated almost infinitely, depending upon the need for precision, throughput, and electronic output. Engineered fixture gages incorporating air jets and/or electronic gage heads can get the manufacturer halfway there, while fully automated systems with parts handling capabilities can ultimately make can gaging a hands-off, closed-loop process.

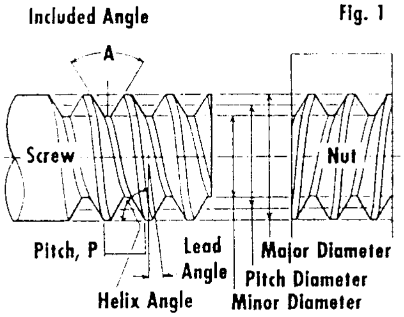
If the only concern is accuracy, then gage design can be pretty simple: laboratories achieve extremely good results with a dial indicator and a comparator stand. Production applications, however, impose additional demands of throughput, ease of use, delivery, and maintenance and mastering intervals. When it comes to cost effectiveness in specialized applications, it's the details that make the difference.

## THE NUTS AND BOLTS OF THREAD GAGING

No pun intended, but thread gaging has always seemed a rather convoluted subject to me. So, when I was questioned on the topic recently, I asked my friend, Lowell Johnson, a recognized authority and president of the Johnson Gage Company, to explain some of the basics and offer some tips on the process. His advice: Don't trust Go/No Go thread gaging. The reason is that this process is still widely used and, despite more than 20 years of evidence to the contrary, is so inaccurate that it will literally allow square screws to fit into round holes. Lowell even demonstrated this in testimony before Congress.

The simple fact of the matter is that tests that only demonstrate whether or not two parts will assemble show nothing about the quality or integrity of that assembly. Just because they go together doesn't mean they are going to stay together. And, in the world of threaded fasteners and components, this can be a critical issue. But why this is so, and why you should be using a system of instrumented dimensional gaging for screw threads, requires some explanation and an understanding of how threaded components function.

Fig. 1



Screw threads are so common we often take them for granted. But in reality, they are geometrically rather complex, as you can see in Figure 1. In addition to material and heat treatment, what gives a threaded joint its strength and integrity is the amount or percent of engagement along the flanks of the mating threads. And because their geometry is so complex, lots of things can happen to limit this contact. Changing the lead angle in either direction will change the pitch and result in mismatched threads. A wobble, or "drunkenness" in the thread helix will limit contact, as will a change in diameter, roundness or taper. Even a change in flank angle will yield a thread which assembles line, but has very little flank contact and almost/zero strength. No matter how hard you try to tighten it, the nut will vibrate loose almost immediately.

To understand the geometrical relationships involved and to allow process control, threads are commonly defined as having two diameters: pitch and functional. Functional diameter is a measure of fit, or the ability of the threaded product to be assembled. This is the only dimension checked by Go/No Go gages.

But as we noted, this may or may not reflect the real “dimensions” of the product, due to the nature of the helix, roundness, lead and taper. Think of a set of gears whose teeth are meshed or butting.

Pitch diameter, on the other hand, is a much more accurate reflection of size. It is defined as “the diameter of an imaginary cylinder passing through the thread profile at such points as to make equal the width of the ridge and the width of the groove. “This number is significant for a couple of reasons. One, the measured value for pitch diameter at any point along the axis of the screw thread reflects the actual amount of thread material. This is called the Minimum Material Size. Second, for design purposes, pitch diameter is the dimensional factor which governs the shear and tensile strength of the thread assembly. It establishes the datum from which variations from perfect thread geometry can be referenced.

This gets much more complicated than we have room to explain, but the important thing to remember is that in a perfect screw thread--and only in a perfect screw thread--the values for functional diameter and pitch diameter are equal. In all other threads, differences in these two values reflect variations in taper, roundness, straightness, lead and thread angle, including helical path. In short, they reflect a smaller percentage of flank area engagement, and hence, a reduction in the performance of the threaded assembly. Likely problems include: galling during installation: joint loosening (due to vibration): leakage: fatigue and relaxation: slip page: and ultimately, failure.

Bottom line, then, is that if you are going to accurately gage screw threads. You need a dual instrument system that measures both functional and pitch diameters. You need to know that both are within specified tolerances and you need to know the value of the difference between them, because it is this number which provides a basis for process control (see illustration).

# CAN'T MEASURE IT? TRY A CALIPER GAGE

If a workpiece has ever left your shop with an important dimension unmeasured because you couldn't get at it to measure it, you probably didn't know about indicating caliper gages. Regardless of the shape of the housing or the complexity of the casting, no matter what size the flange, what curve the tubing, what width the material, or what depth the recess, an indicating caliper gage can give you the desired thickness or inside dimension. Non-destructively, let me hasten to add.

It is important to distinguish indicating caliper gages from the familiar 0"- 6" calipers. These latter, though useful tools, are only capable of measuring the basics -- IDs, ODs, lengths and depths. Indicating caliper gages, on the other hand, use dial indicators. Most have resolutions of .010", and some go to .001". With a range from 0" - 1", or 0" - 3", the indicating caliper gage incorporates a scissors action to facilitate getting around obstructions, and is an immensely useful tool.

The key to the caliper gage's flexibility is its inherently simple hinged geometry: movement at the contacts is mechanically reduced by a gear at the pivot, then re-enlarged the same amount on the face of the indicator. (The ratio is usually 10:1.) As long as that ratio is maintained, the jaws can be essentially any shape you want. They can curve over and around any type of flange, into any curved or angled hole, across long distances, and into the most inaccessible recesses.

The thing to remember about caliper gages is, if you don’t see it, ask for it. Our catalog, for example, lists eight standard gages, but we have engineered -- and I'm not exaggerating -- over 50,000 "specials" for customers ranging all over the board. To design a special caliper gage all a manufacturer needs is a print of the part to be measured, although a sample can also be helpful.

Besides jaw shape, other common options include jaw size (up to 4' long!), body material (aluminum, magnesium, honeycomb composites, etc.), contact shape (ball, blade, rollers), and contact material (carbide, ruby, diamond, plastic). Of course, the indicators come in inches or metric, and any kind of custom dial face can be designed to suit the application. Revolution counters are standard to help you keep track of large dimensions. Because they're fairly simple tools, prices are moderate: most specials cost $700-$800, although prices as low as $500 and as high as $5,000 are not unheard of.

Where would you use an indicating caliper gage? Just a few applications that spring to mind are: housings and castings of all kinds; valve bodies; manifolds; tubing; aircraft components (turbine blades, body and wing components, fuel tanks); wide sheet-type materials (steel, laminates, plywood, composition boards); air-cooled engine cylinder castings (check wall thickness between the fins); and toilets. I know a jet engine manufacturer who has a dedicated caliper gage for every critical dimension on his engine housing castings: literally thousands of gages.

Outside caliper gages measure outside dimensions, such as cylinder or tubing wall thicknesses, flanges, and sheet-stock. Inside caliper gages are often the only way to check inside dimensional features like seal and bearing seats deep inside a casting, recess IDs, or IDs of bent tubing.

Even if your tolerances are relatively coarse fractional numbers that you could measure with a pocket scale or a 0" - 6" dial caliper, or if you currently use a Go/No Go gage, an indicating caliper gage can provide benefits in a production environment. Rather than waiting until you bump up against the next tick on the scale that says you're at your tolerance limit, or worse, make a bad, “No Go” part, the higher resolution and magnification of an indicating caliper allows you to view the trend of your process. You can see if your dimension is getting larger or smaller, be it ever so gradually. This permits you to make adjustments so that you stay near the center of your tolerance range, and avoid the limits altogether.

In sum: Within the limits of their ability to resolve, there's virtually nothing you can't measure with an indicating caliper gage.

## THE VERSATILE SURFACE PLATE

Surface plates provide a broad, smooth, flat reference surface that can be extremely useful for inspecting incoming, in-process, or finished parts. When used in combination with various gages and accessories, such as height gages, gage blocks, angle plates, and squares, they can be used to check a wide range of parameters, including length, flatness, squareness, straightness, angle, feature location, and runout. Surface plates are simple, and extremely versatile.

Surface plates come in a wide range of sizes, from about 12" x 12" to 6' x 12', and weighing up to 10 tons. Three grades are available, the flatness tolerances for each grade varying with the size of the plate: AA (laboratory grade); A (inspection grade); and B (toolroom grade). Many can be ordered with ledges and threaded inserts, both of which make it easier to clamp workpieces or accessories to the surface. Granite is the most common material used: it is harder and denser than steel, has very little internal stress, and is less subject to dimensional change due to temperature variations.

Care and maintenance is basic, but important. A surface plate is a piece of precision gaging equipment, not a storage table. Use it for measurement purposes only, and keep it clear and covered when not in use. Before use, wipe it down with a special surface plate cleaning solution. Make sure that workpieces and gage bases are clean and free of burrs before placing them on the plate. Don't drop anything on it.

Many uses of the surface plate are extremely simple. Some milled or ground parts can be checked for flatness by placing them on the plate and moving them around to see if any rocking motion is possible. If so, feeler stock can be used to find the high spots and measure the variation.

Most often, surface plates are used in conjunction with a portable height stand, supporting a dial or test indicator, or an electronic lever-type gage head. The height stand has a fine-ground base, which allows it to be slid across the surface without scratching. For a simple flatness or parallelism check, the gage is brought into contact with the part and zeroed out. Then the gage is moved around on the plate to "explore" the part surface for deviation. Since the surface plate is the reference, deviation may be errors of flatness, parallelism, or both.

The same setup can be used to check heights, using gage blocks as the height standard. A more sophisticated approach is to use a height master, which combines a permanent stack of blocks, staggered left and right, with a micrometer height adjustment: this allows the user to set both top and bottom heights anywhere from 0" to 12" in .0001" or .00001" increments.

"Smart" height stands can be used to substantially automate measurements on surface plates. Sometimes called "single-axis CMMs," smart height stands consist of a vertical slide with a position encoder, a lever-type electronic gage head and/or touch probe, and an electronic keypad control. They can be programmed to measure many part features and dimensions, including diameters, lengths, and locations, in any desired sequence.

Aside from the measuring devices themselves, a number of positioning accessories extend the usefulness of surface plates. Vee blocks serve as simple holding devices for cylindrical parts. Placed on their sides, they become a clamping surface for shafts, in order to measure the flatness or squareness of the shaft ends. Vee blocks are particularly useful for measuring runout. A part is placed in the vee and rotated, while an indicator or gage head measures the variation in height. (Note that lobes on a round part may create an unstable axis of rotation

If projecting features prevent a part from being placed flat on a surface plate, a parallel bar accessory may be used to bridge across those projections. Sine bars and sine plates are used to establish surfaces at precise angles from horizontal. Angled parts are placed on the angled surface, to check them for flatness, or to measure the angular accuracy of the machined surface.

The surface plate itself can be a gage. A hole is bored in the plate, and a gage head or air jet installed, to inspect flush surfaces for flatness without the use of a height stand. If desired, a second gage head in a height stand can be positioned directly above the one embedded in the surface plate, permitting independent measurements of flatness, thickness, and parallelism.

Surface plates provide a stable reference surface on a large scale, making a great many gaging setups possible on a single, simple piece of equipment. When a gaging application does not warrant the purchase of a special-purpose fixture gage, surface plates often provide an economical, all-purpose solution.

## THE PLANE TRUTH ABOUT FLATNESS

The flatness of machined planar surfaces is often critical to the performance of parts and assemblies. The plane is also the basis, or reference, for most dimensional and geometric measurements, including height, location of features, squareness, and datums. A reference plane may be a feature on the part itself, or it may be part of the measuring instrument, but in either case, the measurement can only be as accurate as the reference. So whether you're making parts or measuring them, you may have to measure flatness.

There are many tools and methods available, depending upon the nature of the part and the degree of accuracy required. Surface plates serve as a general-purpose reference for many flatness measurements. (See *MMS*, July 1995, for more on surface plates.) If the flat surface of the workpiece can be put in direct contact with the plate, it is possible to measure flatness using feeler stock, although this is a low-resolution method, and only the perimeter of the part is accessible. An air or electronic gaging probe installed flush in the surface plate can provide much higher resolution, if the part is small enough to move around on the plate. Each type of probe has its benefits. Air jets are self-cleaning and non-contact, while electronic transducers can be connected with gaging amplifiers or remote indicators with dynamic measuring capabilities, to automatically capture the maximum deviation, or to output data for SPC.

If the part is too big to slide around, or if its configuration is such that the flat surface can't be put in direct contact with the surface plate, then it must be staged. A test stand with a mechanical indicator or an electronic gage head is slid around on the surface plate to explore the part.

This, however, may fail to distinguish between errors of flatness and errors of parallelism. To break out flatness, measurements are taken at equally spaced points on the surface, then the data is plotted on a graph and a best-fit line calculated. Deviations from the best-fit line represent errors of flatness. If the measurements are taken on a vertical surface (using, for example, a "smart" height gage with the gage head turned 90 degrees), one would duplicate the procedure to break flatness out from possible squareness errors.

To measure really large areas, like machine beds or surface plates, electronic levels are often the appropriate tool. Levels may be connected to gaging amplifiers that will automatically convert angular readings into dimensional error. Large areas can also be measured with electronic probes, using a precision straightedge as the reference, as described last month.

With the proper software, the data obtained from large-area flatness measurements can be converted into a 3D plot. This information can be used in at least three ways: the user can do his setups on the flattest areas and avoid the worst sections of the surface plate or machine tool; he can use the data to compensate mathematically for out-of-flatness; and he can use it as a guide to correct the out-of-flat condition.

Optical flats are references for measuring small, high-precision parts, such as gage blocks. Usually made from fused quartz or high quality glass, the puck-shaped optical flat is certified to within 1, 2, 4, or 8 microinches. It is wrung to the part and viewed under a monochromatic (helium) light source. A perfectly flat part will reflect straight, regularly spaced, easily visible interference bands, each representing an interval of 11.6 microinches (the half-wavelength of helium light). Air gaps (i.e., low spots) between the part and the flat will distort the interference bands proportionally to the flatness error: a band that is "bent" by one half its thickness indicates out-of-flatness of 5.3 microinches (1/2 x 11.6). The location of low spots can be identified by the direction of the distortion.

Regardless of the method, before a part can be measured for flatness it is important to know the level of uncertainty in the reference. Flatness may be transferred from certified standards to masters, then from masters to gages, and thence to workpieces, but be aware that the level of uncertainty increases at each step.

## BAR TALK: WHAT'S YOUR SINE?

A few months ago this column described the use of surface plates, observing that a flat surface is the basis for most dimensional measurements. Many workpieces, of course, are neither flat nor straight. In order to measure the angular accuracy or straightness of an angled surface using a surface plate, a sine instrument comes into play. By placing the workpiece on the sine instrument and raising one end of the instrument to the proper height, it is possible to orient the workpiece parallel to the surface plate. Straightforward measurements can then be performed with a test indicator and height stand.

Sine bars are relatively narrow (up to about 1" wide) fine-ground or lapped steel bars, with precision cylinders at each end resting against stops machined into the bottom surface. Some sine bars are completely ambidextrous; others have "upper" and "lower" ends as well as distinct top and bottom surfaces. Holes machined in the instrument enable the placement of stops or clamps to hold workpieces in place. Close cousins to sine bars include sine blocks, which are simply wider sine bars; and sine plates (the most popular version), in which the bottom cylinder is actually part of a hinge connected to an attached base. While most sine instruments serve primarily as measuring instruments, some sine plates are rugged enough to serve as fixturing devices for machining operations. The principle of operation is identical for all versions, so for the sake of simplicity, we'll refer only to sine plates in the following discussion.

To set the sine plate at the proper angle, one simply selects a gage block or gage block stack of the appropriate height and places it under the upper cylinder. An imaginary right triangular prism is thus created, the vertical face of which passes through the gage block and terminates at the axis of the upper cylinder. The horizontal base of the prism is above and parallel to the surface plate, terminating at the axis of the lower cylinder (hinge), while the ends of the hypotenuse are defined by the axes of the two cylinders. The top surface of the sine plate is therefore parallel to the hypotenuse. The use of cylinders as contact points ensures that the length of the hypotenuse remains the same regardless of its angle. Most sine instruments set the cylinders at a fixed distance between centers that is easy to manipulate mathematically, 5" and 10" being the most common lengths.

To calculate the required height of gage blocks, use the following formula:

sin B = b/a where:
B = required angle
b = height of triangle
a = length of hypotenuse.

For example, say we want to measure the straightness of a surface on a workpiece that's angled 27_ from a reference surface on the same workpiece. Let's also say our sine plate is 5" between cylinder centers. To obtain the sine value, we either refer to a table of trig values, or simply punch it up on a $10 scientific calculator.

sin 27_ = b/5"
0.453,990,499 = b/5"
b = 2.270"

So we wring up a stack of gage blocks, place it beneath the upper cylinder of the sine plate, and *voilá*, we have a surface that's 27_ out-of-parallel with the surface plate. We stage the workpiece on the sine plate facing the opposite direction and, if all is well, the workpiece surface should be parallel to the surface plate. We can then measure it for flatness, straightness, and angular accuracy, using conventional surface plate methods. To measure straightness, an indicator held by a test stand is drawn across the surface, and comparative height measurements are taken at regular intervals. By drawing a best-fit line through the data, it is possible to break out the flatness of the surface and to calculate the accuracy of the machined angle.

Because sine values change rapidly between angular measurements of low numerical values, and change very little between higher numerical value angles, the accuracy that can be achieved using a sine instrument varies considerably: precision is much better for shallow angles than for steep ones. Therefore, where the surface of a workpiece is angled at greater than 45_, it is often advisable to use the complement of the angle (90_ - *x*) in the calculation.

Even so, the accuracy that can be achieved with sine instruments is somewhat limited, because there are so many separate mechanical elements to the set-up (the surface plate, the gage block(s), the test indicator, the test stand, and the sine instrument itself), each of which imposes a certain degree of uncertainty. We'll look at methods to perform higher-precision angular measurements in a future column.

## MEASURING TAPERED PARTS

Recently we looked at surface plate methods to measure angles, involving the use of sine plates and indicator stands. By mounting a V-block on the sine plate, these methods can be used to measure tapers on parts such as shafts or conical workpieces. This kind of painstaking layout work, however, is not appropriate for the high volume, tight-tolerance requirements of machine shops. For production-environment measurements of tapered features, other methods are needed.

Common precision tapered male and female parts include features on engine shafts, spool valves, fuel injectors, and needle jets. Among the highest-precision applications are toolholder tapers, and components for orthopedic artificial joints, where tolerances may be in the range of 1–2 arc-sec. or 5–10 microinches per inch. The angular conformance of mating tapered parts can have a major influence on the performance of these assemblies.

As with most dimensional measurements, tapers can be measured with a variety of methods and hardware, offering a wide range of pricing, accuracy, speed, required user skill, numerical capabilities, and other characteristics. We'll start at the low end of the price and accuracy ranges and work our way up.

If numeric accuracy is unimportant, and a general sense of conformance is adequate, one might use a male or female master taper that mates with a workpiece of the opposite gender. This is not a real form of measurement, per se—it's more a form of go/no-go gaging. The master and workpiece are simply mated, and conformance is determined by feel. If bluing dye is placed on the mating surface of the master, it will transfer to the workpiece wherever the two come in contact. This will show whether there is too much or too little taper, and give an indication of out-of-roundness and some other geometric errors, but it provides no numeric results: results are entirely subjective. The precision of this method is quite low—probably on the order of one or two thousandths of an inch—so it's really only good for situations when "close enough" really is close enough.

Air tooling, and fixture gaging incorporating either electronic or air probes, represent a significant step up in capabilities. These are generally custom-built devices, but need not be expensive, for most of them are quite straightforward. Probes or air jets are arranged to measure two or more diameters on the tapered feature at a known distance or height from one another. Female tapers can be measured using tapered air plugs, as shown in schematic form in Figure 1, while male tapers that appear at the end of a workpiece can be measured with tapered air rings.

Sometimes it is lack of taper that is important. Crankshaft journals, for example, must be checked to ensure there is no taper, barrel, or hourglass shape. This is best performed with a fixture gage, which holds the shaft in V-blocks or centers, while two or more pairs of electronic or air probes measure the journal from opposite sides. Mechanical indicators can also be used, but this is becoming less common as the requirements for speed and high precision increase. Today's amplifiers and air systems, with their computing and output capabilities, have all but replaced the mechanical indicator for these fixture gaging applications.

Normally, this methodology involves comparative measurements, in which an accurately machined taper generates a reading of zero on the gage, and deviation from nominal is shown as the sum of the deviation, in opposite directions, of the two measured diameters. In other words, if the larger diameter, Diameter 1, is 0.0001" over nominal, and the smaller diameter, Diameter 2, is 0.0002" under nominal, the gage will read total deviation as +0.0003". On the other hand, if Diameter 1 is 0.0001" over and Diameter 2 is also 0.0001" over, then total deviation in the taper is zero: there may be a machining problem in holding the diameters to spec, but the taper itself is accurate. Many gaging amplifiers can readily convert gaging input into absolute, as opposed to comparative readings, and present the results in units of arc-sec., or microinches of error per inch of tapered height.

Comparative-measurement tooling and fixture-type gaging represent the best methods for use in production environments, in terms of price, throughput, ruggedness, and environmental stability. Very little operator skill may be required, depending upon details of the gaging amplifier or other input/output options.

Naturally, these methods require very accurate masters. In order to check the masters, an even higher level of accuracy is required, which can be achieved with a master-ring-and-disc comparator. This is similar in principle to a typical benchtop ID/OD gage, but raised to a very high level of technical refinement, with precision to 1 microinch possible in a controlled environment. By raising or lowering the instrument's jaws, diameters can be checked at two or more heights; then a simple trig function is applied to calculate the taper. This type of gage, which is normally confined to laboratory use, tends to be on the pricey side, and is engineered for accuracy rather than throughput as the top priority.

## DEPTH GAGES

Depth gages are among the simplest of indicator gages, typically consisting of an indicating device mounted through a reference bar or plate. Though they may be simple, depth gages are used in thousands of critical applications, to measure the depth of holes, counterbores, slots, and recesses, as well as heights or locations of some features.

The first depth gages consisted of a simple rule with a sliding perpendicular beam as the reference. As the needs for higher resolution and precision increased, these were largely replaced by vernier devices and micrometer depth gages. And while both verniers and micrometers remain in wide use, indicator depth gages provide even higher levels of accuracy, as well as increased speed of operation and lower dependence upon operator skill.

As with almost all indicator gages, depth gages can be readily modified to suit particular application needs, especially to make high-volume gaging tasks quicker. Depth gages are available with various styles of indicators, contact points, and bases.

The simplest and most common depth gage has a flat base or anvil, a sensitive contact that retracts flush with the base, and a radiused contact point. This is an absolute gage, measuring the full depth of a feature, from zero out to the indicator's maximum range. No master is required: to zero the gage simply set the base on a precision flat surface.

Different contacts can be used to tailor the gage to special applications. For example, by replacing the standard radiused contact with a needle-style contact, it is possible to measure surface pits, small holes and recesses, and etch depths.

Extended contact points can be added to measure greater depths, or to turn an absolute-measuring gage into a comparative gage. Such a gage can be mastered with gage blocks by holding one end of the base firmly on top of the stack, with the spindle as close to the stack as possible without interference. Special depth masters, however, are quicker and more reliable, and are thus more practical for production gaging applications.

Special bases can also increase gaging efficiency. Counterbores may be gaged more easily if the indicator is offset from the centerline of the base. V-shaped bases are useful in applications where a standard flat base would interfere with the user's ability to locate a needle-type contact in a small feature, such as a pit or an etched line. The V-base provides a wider viewing angle, but still has a narrow "flat" on the bottom to help orient the gage perpendicular to the part surface. The user first tips the V-base on the workpiece surface, locates the contact point in the feature, then "rolls" the gage upright until it rests on its flat.

Custom anvils can be readily designed to conform to the shape of the workpiece. Take, for example, the aerosol can. This is a metal part that is literally under pressure, and so is liable to more potential failures than most types of containers. The depth of the crimp groove is a critical quality dimension that must be carefully monitored. Depth gages designed for this application with special bases that rest securely on top of the can have proven themselves ten times faster in use than generic vernier depth gages.

All of the gages described above are portable or hand-held designs, which implies bringing the gage to the workpiece. It is often convenient, however, to bring the part to the gage, especially if the part is small. Benchtop depth gages essentially turn the portable gage upside-down, and provide a wide flat reference surface—virtually a table—upon which the workpiece can be placed and manipulated. Parts can also be "explored" for flatness with this type of gage, by sliding the workpiece around on the table.

Users can also choose among indicator styles. Long-range indicators, with revolution counters, can measure depths from 0" to several inches (or their metric equivalents). Special indicator faces can be designed for "stoplight" gaging, with green, yellow, and red segments to quickly signal good, marginal, and out-of-tolerance parts. Indicators with "push-down" movements allow users to locate the contact point against the workpiece more positively than is possible with conventional "sprung-down" indicators. Gages can also be equipped with digital electronic indicators, providing opportunities for dynamic measurements (such as automatic capture of minimum or maximum readings), and data output.

Rules for depth gage use are straightforward. Both workpiece and anvil must be clean and free of burrs. For portable gages, the base must be held firmly against the workpiece, and it must be positioned flat and square. As with all indicator gages, accuracy also requires a rational mastering schedule, the frequency of which depends upon the amount of use, as well as the conditions in the gaging environment.

## GOT A MATCH?

Producing precision spools and sleeves (e.g., for fluid pumps) and other pairs of parts with matching inside and outside diameters can be among the trickiest of quality issues. It’s very easy for an engineer to specify that the outside diameter (O.D.) of the one and the inside diameter (I.D.) of the other must be within .000025” -- and less easy for a machinist to accomplish.

You can spend days trying to tighten up your processes to meet those specs consistently, and chances are you’ll still end up tossing or reworking a high percentage of your production. The solution to the problem may lie not in the process, but rather, at the QC end. Maybe you can loosen up on your process, and measure your way out of the problem with match gaging.

When an engineer specifies tolerances for spool and sleeve diameters, what is his real concern? Is it absolute dimension? Likely not. In an application like a fluid pump, or a fuel injector, it’s the clearance between the two parts that determines how well it functions. That’s where match gaging comes in. Match gaging doesn’t measure diameters: it measures the clearance (or interference) between two parts. It can be a tremendous time- and work-saver where a desired amount of clearance or interference is required.

In its simplest form, match gaging uses an air gage with a two-legged manifold, one leading to an air plug, the other to an air ring. To measure a match, place the O.D. part (spool) in the ring and the I.D. part (sleeve) on the plug. The gage indicates the total of the clearances between the two parts and their respective fixtures.

Match gages are available in a wide range of configurations from simple manual gages to highly complex, fully automatic, multi-measurement gages costing many thousands of dollars. In terms of accuracy, they are available with 50 millionths resolution and a range of 0.003" at the coarsest, to 5 millionths resolution and a range of 0.0003" at the finest.

The greatest advantage of match gaging is that it allows you to produce matching parts at extremely tight clearance tolerances without actually having to achieve the same level of precision in the machining process itself. To see how that works, let's look at a set of parts with a nominal size of 1.0000" and where engineering has calculated that optimal performance requires a clearance tolerance of between 100µinches and 200µinches.

There are basically three ways of achieving this desired fit between matched components. The first involves controlling the size of both parts to assure an accurate match and full interchangeability. This method tightens the manufacturing process severely and necessitates machining to a plus tolerance on the O.D. part and a minus tolerance on the I.D. part, as follows:

| **Outside Diameter** | **Size Tolerance** |
|---|---|
| 1.000100" | +0.000050"/-0.000000" |

| **Inside Diameter** | **Size Tolerance** |
|---|---|
| 1.000000" | +0.000000"/-0.000050" |

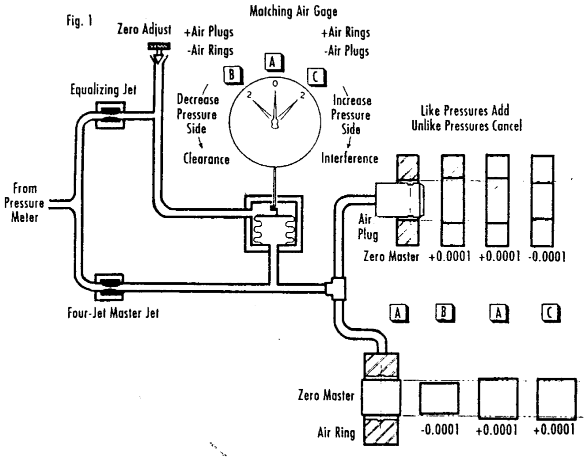
The second method is to control the size of one component where the other is predetermined by a previous process. Typically, the O.D. is the fixed measurement (in this case, 1.0000" ±0.0001") and the I.D. is then machined to fit. Air gaging is used to assure the 100µ inch to 200µ inch clearance between parts. This method usually requires maintaining a substantial inventory of O.D. parts and often involves a cumbersome measuring process.

Match gaging gives us a third alternative: we can machine both components, allowing the tolerances to vary as they will, and use the match gage to select matched sets. Thus, the O.D. is machined to 1.0000" ±0.0005" and the I.D. to 1.0000" ±0.0005". Assuming a normal distribution curve from our machining process, we can use a match gage (often automatic) to select sets which fall within our 100_ inch tolerance range.

Some users may elaborate on this process. For example, a manufacturer of fuel injectors had a clearance tolerance range of 20_ inches between barrel and spool. They were unable to control the machining process to produce either part consistently within that range, but a fully automatic match gaging setup now allows them to stage, match, assemble and package 700 pairs per hour. Feedback from the gage is used to control the processes, letting the distribution of spool O.D.s move up or down to accommodate an overabundance of barrel I.D.s at one end of the scale or the other. Both ranges are allowed to float, chasing each other up and down the scale to assure enough matching spools and barrels to maintain production rates.

*A matching air gage is an effective way to find parts that meet specified clearances between them.*

Fig. 1



## IN THE GROOVE

It just might be easier to manufacture a groove on a turned part than it is to inspect it. Select the right cutting tool, set the CNC, and *bada-bing bada-boom*! you're done. (Okay, I exaggerate.) But because of the critical functional role played by grooves for seal rings and retainer rings, good gaging practice is a must. There are many different gage types from which to choose, and because inside grooves tend to be more difficult to measure than outside grooves, we'll examine inside groove gages more closely.

The pistol-grip or linear-retraction style groove gage is specifically designed for inside grooves. It features long retraction of 1/2"/13mm, which enables it to fit inside the bore, then expand to the full depth of the groove. The indicator's sensitive range is usually much smaller than the retraction—on the order of 0.040"/1mm, which is more than adequate for the expected variation in most precision applications. The indicator may be either dial or digital, and usually has resolution of 0.0005"/0.01mm. The lower contact is a fixed or reference contact, to bear the weight of the gage; the sensitive contact is located above, where it is unaffected by the weight.

Contacts tend to be built robustly, to resist flexing when the gage is "rocked," in the same manner as other bore gages. Procedures for mastering, too, are similar to those used for bore gages, except that a fine adjust is usually provided on groove gages, to simplify zeroing.

Contacts are adjustable over a range of 2" to 4" (25mm to 50mm), so that different size parts may be inspected with a single gage. Another important characteristic is the interchangeability of contact tips. Extra-long contacts permit access to deeply spaced grooves, and special contact shapes allow inspection of grooves right up to the shoulder, and of round- and V-bottom grooves.

Inside-measuring swing-arm or caliper gages are general-purpose instruments that may be applied to a wide range of inside dimensions, including inside grooves. Caliper gages can measure through their entire retraction range, which is often over 3/4"/75mm. These gages can therefore measure features where variation is expected to be large, and can measure different size parts without adjustment. On the other hand, because they are non-adjustable, their ultimate range and flexibility may be poorer than pistol-grip style gages.

When choosing between linear-retraction (Fig. 1) and caliper-style (Fig. 2) gages for inside-diameter groove measurements, users must weigh issues of range, capacity, ruggedness, accuracy, and cost.

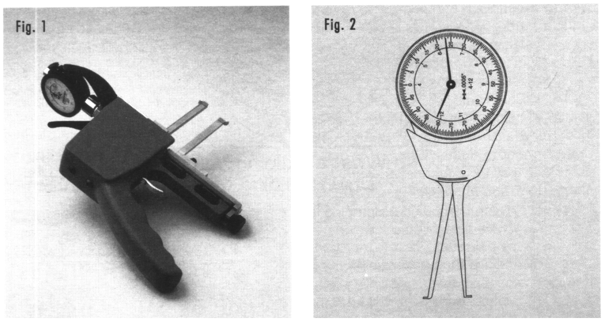


Fig. 1

Fig. 2

Because of their long range, caliper gages have dial indicators with secondary dials, or revolution counters. Some users have trouble reading these dials accurately. One way to bypass this problem is with a digital caliper gage, although these are not very common.

Rocking a caliper gage side-to-side for axial alignment tends to stress the caliper arms and pivot, and is not recommended. As a result, caliper gages may not produce results as accurate as pistol-grip gages, which are engineered to promote rocking. On the other hand, caliper gages are lighter, smaller, less expensive, and easier to use, all of which makes them quite popular. They also offer a greater variety of contact styles for access to difficult features.

Compared to inside grooves, outside grooves are a snap. They are normally measured with a snap gage fitted with special narrow anvils, called blade anvils, which are available to match the depth, width, or shape of any groove. With their heavy spring pressure and rugged positioning backstops, snap gages do not need to be rocked, and are very easy to use.

Finally, bench-type ID/OD comparators can measure inside and outside grooves if fitted with special contacts. ID/OD comparators offer the highest potential accuracy, and allow the part to be rotated, to explore the groove for minimum or maximum readings. But they are limited to use with small, portable parts, with grooves less than 1"/25mm from the mouth of the bore.

## "SQUEEZE" GAGING

Machinists working strictly in metal-working shops do not have many occasions to gage the thickness of soft materials. But many of our readers work in supporting roles, helping to build or maintain the machines that produce textiles, plastic films, paper and other products that are compressible. Even readers who work only with metals should realize they are not alone in their concern for accuracy: the shirt on your back, the newspaper you read this morning and the garbage bag you tossed it in, were all produced to exacting thickness tolerances.

Differences in gaging pressure translate readily into differences in the degree to which the sensitive contact compresses or penetrates the material being gaged. It is, therefore, essential to use a standardized method when measuring the thickness of compressible materials. Every industry and every kind of material has its own standards, most of which have been established by the American Society for Testing Materials or by Underwriters' Laboratories. These standards specify the size of the reference table and the measuring contact (or foot), the dial gradations, and the amount of force to be used. (Gaging force is controlled by a weight, rather than with the springs found in most dial indicators, to ensure consistency of compression). Such standards make purchasing decisions quite straightforward: often, you need only specify which ASTM standard you wish to meet.

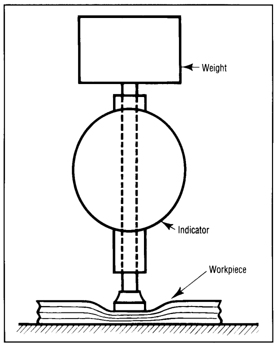
Assuming you have the right gage for your material, making accurate measurements of compressible materials is not difficult if you follow a few basic guidelines:

### The Anvils Must be Parallel

If they are not, they will compress the material at an edge rather than across a flat surface. To check for parallelism, close the contacts and try to shine a flashlight through them. Parallel contacts allow no light to shine through; any lack of parallelism is readily apparent down to about 0.0001". Check front to back, and side to side.

It is difficult to hold larger contacts -- say those above 1/2" x 1/2" --in alignment with the light source. And the visual method may fail to reveal problems such as an upper foot with a worn center or a chipped edge.

*When gaging compressible materials, differences in gaging pressure translates readily into differences in the degree to which the sensitive contact compresses the material being gaged. To ensure consistency of compression, gaging force is controlled by a weight, rather than with the springs found in most dial indicators.*



If you need more accuracy, or if visual inspection reveals a lack of parallelism and you want to measure it, use this method: Place a precision wire of 0.010" or 0.020" diameter under the front edge of the upper foot, and zero the indicator. Then retract the contact, place this "master" under the rear edge, and repeat the measurement, noting the variation. Repeat for left and right sides also.

Some gages have machine screws to adjust the reference table into parallel with the upper foot. On those gages that do not, the common solution is to file down either the boss that holds the indicator to the frame, or the shoulder against which the reference table support is clamped. Easy does it!

### Make Sure Contacts Are Not Contaminated

This is a common source of error. As in any gaging procedure, the contacts must be kept clean of dirt, lint or hair. When measuring materials such as polyethylene film, which may have been in liquid form only minutes before, beware of the buildup of chemical deposits on the contacts. As with any textile product, frequently clean lint off the contacts.

***Check for Gage Repeatability By Checking Several Points on the Surface of a Known, Consistent Sample***

Most gages for thin materials do not need to be mastered. Simply “zero” the gage against the reference table. To avoid having to count dial revolutions when measuring thicker materials like acoustic tiles or carpet, use a gage block to set the zero at the nominal dimension of the material.

If a gage reads “under”, the problem is most likely a lack of parallelism. If it reads “over”, dirt is probably the culprit. Of course, other factors common to all gaging, such as friction in the mechanism or a loose fixture, can also be at fault.

## USING AND MEASURING PRECISION BALLS

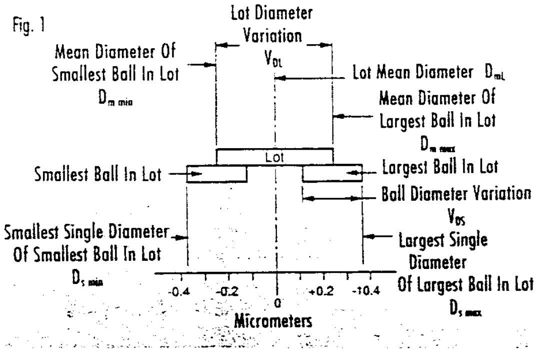
Balls are an integral part of every machine shop. They are found in bearings for both rotary and linear motion applications in machine tools; they act as contacts and pivot points in gaging equipment and tooling; and they serve as masters for both size and roundness gaging.

Balls are especially useful to check the parallelism of surfaces on gages with flat anvils and sensitive contacts, including many thickness gages and snap gages. The procedure is simple enough: Pairs of measurements are taken with the ball at the anvil's 3:00 and 9:00, and 6:00 and 12:00 positions, and the anvil is adjusted accordingly.

But in order to perform this function, it is first necessary to confirm the dimensional accuracy of the ball. As with most dimensional standards, the accuracy of a precision ball should be roughly ten times greater than the resolution of the gage which it is used to master, and the instrument used to measure the balls should be ten times are accurate as they are. Consequently, balls are commonly measured to microinches, or even fractions of microinches.

Comparator gages used to measure balls must not only measure in millionths -- they must also measure to millionths. They must be designed to the highest standards of stability and precision. As shown in Figure 1, the lower anvil of a ball gage is adjustable for parallelism with the sensitive contact. A frictionless mechanism may be used to ensure constant gaging pressure, and a V-notched saddle may be installed on the anvil to locate balls, with the help of a few degrees of backward tilt. The gage must be in a controlled environment appropriate for microinch measurements, with measures taken to guard against contamination and thermal influences.

Fig. 1



Some users like to force the ball between the contacts, reasoning that the pressure tends to "wipe" away any dust or oil that could skew the measurement. Others prefer to retract the upper contact with a lifting lever before placing the ball on the stage, believing that this ensures consistent gaging pressure between trials and reduces stress to the mechanism. The jury is out on this one, so take your pick.

Now, what are we measuring for? When we specify a ball, we are usually concerned with its nominal diameter (D): the value by which it is identified, e.g., 1/2", 12 mm, etc. Within the range of its manufactured tolerance, this should coincide with the ball's single diameter ($D_S$), the distance between two parallel planes tangent to the ball's surface -- in other words, the results of a single gaging trial.

No ball, however, is perfectly round, and no two balls are perfectly identical. When using balls as gage masters, it is important to establish the level of uncertainty. To accomplish this, individual balls are measured several times, at random locations, to find minimum and maximum diameters. The difference between these, known as ball diameter variation, is simply calculated as follows: $V_{Ds} = D_s \max - D_s \min$.

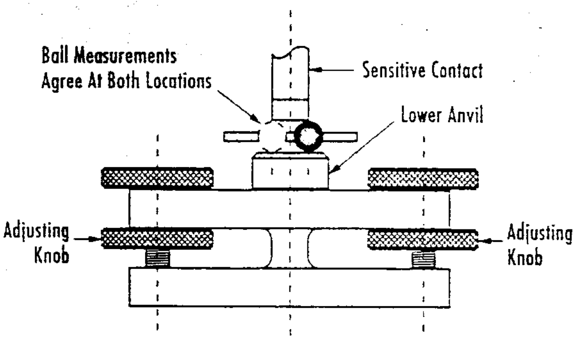
Manufacturers of balls, and OEMs who purchase balls as components, utilize several additional parameters for quality control, and to sort balls into quality groups. Another basic parameter is ball mean diameter ($D_m$). This is the arithmetic mean of the largest and smallest single diameters of a ball, calculated thus: $D_m = (D_s \max + D_s \min)/2$.

To account for production variation between units, manufacturers typically measure balls in lots of ten. Calculations of lot mean diameter ($D_{mL}$) and lot diameter variation ($V_{DL}$) are based on the mean diameters of the largest and smallest balls in the lot, as follows:

$$D_{mL} = (D_m \max + D_m \min)/2$$
$$V_{DL} = D_m \max - D_m \min$$

See Figure 2 for the relationship between individual balls and lot measurements.

Fig. 2



All of the above are static measurements that can be performed using straightforward comparator gaging equipment. Bearing manufacturers, who require orders-of-magnitude more data in order to predict performance under dynamic conditions, perform additional measurements using circular geometry (roundness) gages. These can generate least-squares circles, analyze waviness geometry in a velocity-proportional fashion, and perform harmonic analysis to predict the "noise" effects of part geometry at various speeds and under various loads. These methods are beyond the scope of what we can cover here. But for most machine shops, who use balls mainly as measuring standards, highly precise comparator gages can provide all the data necessary to ensure accuracy.

## TEMPERATURE COMPENSATION

Temperature variation is one of the most significant sources of gaging error. As manufacturing tolerances get tighter and the margin for gaging error gets smaller, it becomes an issue that must be addressed.

Most materials expand as they heat up. For every inch of steel, a 1°F increase causes expansion of approximately 6µ". For brass and copper, the figure is 9µ", and for aluminum, 13µ". If the objective of the inspection process is to determine a part's true size, its temperature must be known. Based on the ISO's very first standard (ISO 1 issued in 1931), that temperature is automatically assumed to be 68°F (20°C).

But few inspection processes monitor, much less attempt to control, workpiece temperature. Many quality managers assume that any thermally induced variation in the part will be matched by like variation in the gage and the master: everything will expand and contract at the same rate, and everything will work out just fine.

This is far from true. Gage, master, and part—the three hardware "components" of a gaging system—may be of different materials, so the effects of thermal expansion will differ even if they're all at the same temperature. And the components won't necessarily be the same temperature. Parts that have recently come off a dry machining process may be several degrees warmer, and may remain so for hours. Parts machined under coolant may be cooler. The gage or the master might be sitting on a bench in direct sunlight, or under a heating or cooling vent. Temperature stratification within a room may create temperature differences between components placed near the floor, and components placed on a high shelf. The relative masses of the components may make a difference. For example, an engine block may take longer to reach equilibrium with ambient temperature than a bore gage. And in some instances, thermal variation may work in opposite directions for the gage and the workpiece, compounding rather than canceling the error. For example, high temperatures will cause bore gage contacts to grow longer, which will naturally result in ID measurements that are smaller than actual. On the other hand, the ID of a thin-walled part, like a bearing shell, will grow larger with higher temperatures.

These errors can be significant. As an example, let's use an aluminum part with a critical dimension of 4.0000", and a steel master to zero the gage. The shop is hot today, but both the part and the master are at equilibrium at 80°F (or 12°F above "standard"). Master and workpiece have expanded as shown:

Steel Master: 6μ" x 4 x 12 = .000288"
Aluminum Workpiece: 13μ" x 4 x 12 = .000624"

Error caused solely by the different coefficients of thermal expansion for the different materials is .000624" - .000288" = .000336". That's significant in most operations.

Now assume instead that shop temperature is a perfect 68°F and that master and gage are both at ambient, but the workpiece just came off the machine, and it's 80°F. The entire .000624" variation in the part will show up as measurement error!

Some companies attempt to control this problem by trying to control the environment. Typically, this involves installing sophisticated HVAC controls and building modifications; allowing time for workpieces to reach equilibrium prior to gaging; and other elaborate measures. This works in metrology laboratories, but it's futile in machine shops. The buildings are too large, with too much surface area and internal volume, too many heat-generating devices cycling on and off—too many variables altogether. Essentially, you would have to turn the shop into a controlled lab environment—and that would be really expensive!

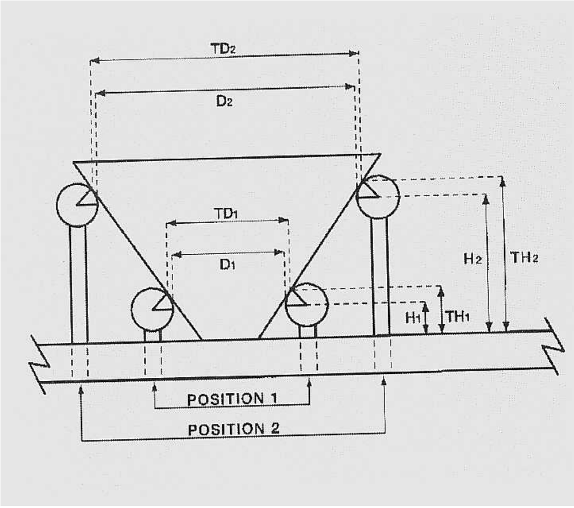
A better approach is to measure the temperature of the part, master, and workpiece, and compensate for thermal variation based on the known coefficients of expansion. This is now practical on a production basis using special devices like those from Albion Devices, Inc., (Solana Beach, CA), which interface with electronic gaging systems. Typically, two small, industrial-hardened sensors are installed on the gage: one to measure the temperature of the gage itself, and one to measure the workpiece or master when either is staged. The system can be programmed for different coefficients of expansion of the various components, and the results are fed into an algorithm which generates a temperature-compensated measurement result on the gage readout. (Additional compensation factors may be built into the algorithm, to correct for unusual elements in gage geometry, differences between a workpiece's surface and interior temperatures, and similar variables.) Such a system will typically reduce thermally induced errors by 90-95 percent. In our second example with the aluminum workpiece, that would bring the error down to 62μ" or less—a figure most shops can live with.

## INSPECTING TAPERS
## PART 1: CERTIFYING THE MASTER

Conical parts, such as machine tool tapers (i.e., tool holders), gas petcocks, and the shanks of modular prosthetic joints, must often be inspected for taper accuracy. This is usually performed with a special air or electronic gage, custom-made for the specific part. The gage is configured as a female counterpart of the conical part, with air jets or electronic probes located inside at two or more known heights. The gage essentially measures two or more diameters on the tapered feature, calculates the difference between them, and expresses the results either in angular units (e.g., degrees/minutes/seconds or thousandths of degrees), or as deviation from a specified slope (e.g., change of diameter in inches, per foot of length).

Tool holders are of particular interest, because the accuracy of the taper affects the quality of the parts they are used to manufacture. According to ANSI standard B5.10, V-flange tool holders are built with a specified rate of taper of 3 1/2" per foot, +0.001"/-0.000. ISO standard 1947 defines a number of taper grades, and establishes different tolerances depending upon both grade and taper length. Regardless of which standard is followed, it is necessary to master the gage before it can be used to measure parts. The taper master is typically a more precise version of the part but, before it can be used to master the gage, it must be certified.

ANSI's 0.001"/ft. tolerance seems easy enough to achieve until you look at the complexity of the inspection process. First, most toolholders are much shorter than 1 foot, so most gages actually compare diameters that are just 3" or 4" apart. Taking 3" as an example, the part has to meet a gaged tolerance of 0.001" ÷ 4 = 0.00025". Using a standard 10:1 ratio, the gage master should be accurate to 25 microinches, and the gage should resolve to the same amount. To certify the master, again at 10:1, will require a ring and disc comparator or a universal measuring machine (UMM) that resolves to 2.5 microinches. A controlled laboratory environment is essential to achieve that level of accuracy.



Certifying the master roughly replicates the production measurement process. The diameter of the master is measured at two known heights, and the slope or angle is calculated from the results. The comparator or UMM is fitted with ball or roller contacts, respectively, whose diameter is known. Because straight-sided gage blocks are used to master the gage (both vertically and horizontally) for measurements on a tapered part, trigonometry is required to calculate the differences between the points at which the mastering occurs, and the points at which the gage contacts touch the tapered part.

Using gage blocks, a very precise indicator, and a height stand, set the height of the tops of the contacts so that the contacts will touch the master at the same height as the lower contacts in the production gage ($TH_1$ in the diagram). Next, use gage blocks to master the distance between the two contacts, again accounting for the "error" between the mastering points of contact (at $D_1$), and the measuring points of contact (at $TD_1$). Then measure the taper master at $TD_1$.

Using the same procedures, reset contact height and spacing in order to measure the master's diameter at the same height as the upper contacts in the production gage ($TH_2$). Calculate the angle or slope of the master from the data obtained. Note that the master must be staged absolutely vertical on the comparator or UMM. Prior to certifying the master, a circular geometry gage could be used to check the squareness of the master's end face to its axis.

Certifying taper masters is not for the faint-hearted. Operating within the realm of single-digit microinches, it requires the use of special instrumentation and methods in a lab environment, and a command of trigonometry.

Once the master is certified, however, it can be used to "zero" the production gage, whose use is somewhat easier. We'll look at how to measure tapers on a production basis next month.

## GAGING DISTANCE BETWEEN HOLE CENTERS

Many of the gaging applications we've considered over the years involve size inspection of a single feature, e.g., the diameter of a hole, depth of a groove, height of a gage block, etc. Many parts, however, contain multiple features that establish dimensional relationships between two or more other parts. Examples include engine blocks, with multiple cylinder bores that establish distances between pistons, and pump housings with two overlapping bores that establish clearance between two mating impellers. As with people, machined features tend to be simple and straightforward when they're single. When people or parts are in relationships, however—and especially when those relationships involve mating—things can get complicated.

Gaging the distance between hole centers is a good example, because it requires that you first locate those centers in space before you can measure the distance between them. Gaging equipment may vary widely with the application, and include considerations of part size and configuration, and required throughput and accuracy. But the basic idea remains the same across various technical approaches; you must first establish references between the part and the gage, often in three dimensions, before you can measure deviation from a specified distance between features.

A basic approach is a hand-held gage, like that shown in the figure. Both of the plugs have two fixed contacts, and one spring-loaded contact each, so they automatically center themselves in their respective holes. One of the plugs is a fixed reference; the other is a sensitive contact. Note also the hard depth stops, establishing a reference in the third dimension. The sensitive plug moves relative to the fixed plug on a frictionless device such as a pantograph mechanism or an air-bearing carriage for good repeatability. The sensing/indicating device used to measure deviation may be a simple dial or digital indicator, or an electronic probe and amplifier.

This gage is economical, reliable, and easy to use. It may be employed with parts as large as an engine block (or larger), or as small as a connecting rod, and its capacity may be adjustable to measure different distances. The plugs may be replaceable, to accommodate different size holes. Its limitation is that it only measures distances between centers; no other types of features or relationships may be checked.

The next option is a gaging fixture engineered for a specific part. Such gages are generally benchtop devices, so they are limited to use with relatively small parts (e.g., automotive conrods) that can be brought to them. The workpiece is typically located over fixed plugs, each of which may contain one or more air or electronic probes as sensing devices. Fixture gages may offer limited adjustability, but tend to be very application-specific.

The benefit side of the coin, however, is substantial. Fixture gages tend to be very stable, and allow high throughput rates. Because the probes can be spaced quite densely within the fixture, it is possible to measure multiple features or characteristics simultaneously. For example, a conrod gage with sixteen probes (eight each for the wrist pin and the crankshaft bores) can be engineered to measure the following features, in addition to center distance between bores: four diameters per bore (6:00 to 12:00, and 3:00 to 9:00, at both top and bottom), bore "out of roundness" (i.e., the difference between two diameters at right angles), bore taper, and bend and twist between bores. Gaging computers and some amplifiers can be readily programmed to perform all these measurements without changing the gaging setup.

For large, mass-produced parts with multiple features in relationship (such as engine blocks or cylinder heads), an elaborate "doghouse" gage may offer the best combination of accuracy and throughput. The gage gets its name from its large, cast-iron structure that contains machined reference surfaces and "sweep" gage plugs, and establishes precise relationships between them. The engine block is pushed into the doghouse, and reference surfaces on the workpiece are positioned against matching references in the gage. The sweep gages are single-probe gaging plugs that are mounted in bearings, and may be rotated 360° on their axes to establish the locations of the hole centers. Operation may be either manual or automatic.

In an automated gage, multiple sweep gages descend simultaneously into the appropriate bores. A gaging computer then takes the data and calculates the multiple relationships between the bores. This may even include not only distances between adjacent bores, but also distances between opposite banks of cylinders on V-configuration engines. Results may be presented in numeric and/or pictorial displays.

Obviously, such a gage is costly, and must be engineered for the specific application. It is often justified, however, in automotive and similarly high-volume/high cost applications where multiple relationships must be measured to high levels of accuracy at very high rates of throughput. And in essence, it's not very different from the simple hand-held gage; the basic idea is still to provide a means of reliably locating the workpiece against fixed reference contacts, then measuring deviation relative to those references.

## GAGING "RELATIONAL" DIMENSIONS

Specifications often require inspection of dimensional relationships between two features, or between two dimensions on the same feature. For example, a TIR (total indicator reading or total indicated runout) specification defines a relationship between the outside diameter of a part feature, and the part's axis. The taper of a conical part is another relational specification, which is checked by comparing diameters at two known heights. Other examples include distance between centers, ID or OD ovality, and parallelism.

Compared to single-dimension specifications (such as diameter), these "relational" specifications can be challenging to inspect. Not only do they involve multiple measurements; they also require that separate measurement results be somehow combined in a mathematical relationship. This might be as simple as subtracting the minimum reading from the maximum reading, as in the case of ovality, or so complex as to require trigonometry, as in the case of taper measurements.

Of the three standard gaging methods available for these tasks—indicator gaging, electronic gaging, and air gaging—air possesses the best combination of properties for most applications. Dial indicators are somewhat bulky, restricting the close spacing of contacts. And to combine the results of two or more measurements, the operator must usually perform mathematical calculations. While electronic gaging amplifiers can be readily programmed to combine signals from multiple contacts and calculate results directly, many electronic gage contacts are too long to be placed in tooling for inside dimension measurements.

The type of air gage known as a dual-circuit air comparator (also known as a differential, or balanced, gage) has a circuit working on either side of a bellows in such a way that the gage reads zero when pressure in both circuits is equal, while any differential between the circuits is displayed as variation from zero. With appropriate tooling, this arrangement allows the gage to combine signals from multiple jets, to generate relational dimension results directly. In addition, air jets are quite small, permitting great flexibility in gage design, especially for inside measurements.

The diagrams show schematically how jets are arranged in tooling to measure various relational dimensions. As shown in (A), a conical taper gage places pairs of jets on separate circuits, to compare two diameters at known heights. Gage (B) measures wall thickness variation, or eccentricity of ID to OD. The tooling in (C) measures bore squareness, while ignoring bore diameter and taper. Two such tools could be combined in a single fixture to measure bend and twist of two bores relative to one another, or bore parallelism in two planes.

Gage (D) measures the center distance between bores by comparing distances between opposite walls of the bores, while ignoring changes in bore diameter. Gage (E) measures ovality by comparing two diameters in the same plane, at 90 degrees to one another. And gage (F) measures parallelism by comparing part thickness at two locations.

Another common "relational" inspection task (not shown) is the measurement of clearance between mating parts, as in fuel injector and bearing assemblies. We can't squeeze a gage between the assembled components to measure clearance directly, but we can measure two unassembled parts simultaneously, using one gage circuit for the ID component, and the other for the OD component. The gage will thus display the "match" or clearance. Should it indicate that clearance is out of tolerance, we can leave the OD part on the tooling, and inspect a number of ID parts until we find a proper match.

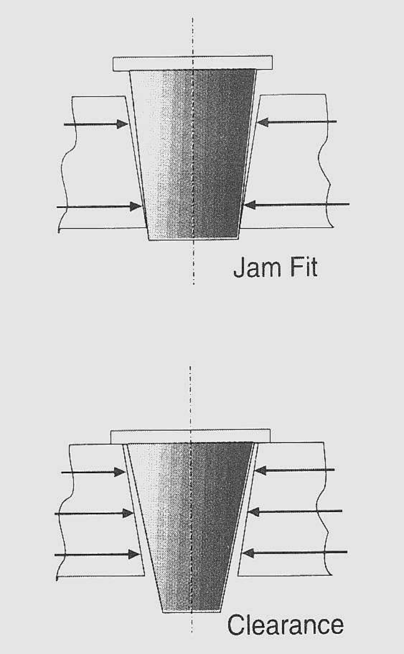
It is often useful to obtain simple, single-dimension measurements simultaneously with relational measurements. For example, in addition to inspecting wall thickness variation in (B), we may also want to measure the outside diameter. Air gaging excels at this task. In all the examples, additional jets could be installed in the tooling, adjacent to the ones shown. These new jets would run on separate air circuits to a second comparator, to perform simultaneous measurements of diameters (in diagrams A through E), or thickness (F). In many cases, the tolerance for the "relational" dimension will be significantly tighter than the tolerance for the "simple" dimension. If this is the case, we can specify different levels of magnification for the two gages, each one suited to the range and resolution required.

## INSPECTING TAPERS, PART 2: TOOLHOLDER GAGING

A few months ago, we discussed the calibration of conical taper masters, which are used to master taper gages. Now let's look at the parts those gages are used to inspect: toolholders.

The most common type of toolholder for CNC machining is the CAT-V or V-flange type. CAT-V toolholders are external tapers, typically available in five common sizes: 30, 40, 45, 50 and 60. These numbers define both the gage line diameter and length. All sizes have the same included rate of taper of 3 1/2" per foot.

There are many reasons for the popularity of V-flange toolholders. One advantage is that they are not self-locking, but are secured in the spindle by the drawbar—an arrangement that makes tool changes simple and fast. They are also economical, because the taper itself is relatively easy to produce, requiring precision machining of only one dimension: the taper angle.



The toolholder must properly position the cutting tool relative to the spindle and, when secured in place, must rigidly maintain that relationship. The accuracy of the tapered surfaces on both the toolholder and the spindle is, therefore, critical.

If the toolholder's rate of taper is too great, there will be excessive clearance between the two surfaces at the small end of the taper. If the rate of taper is too small, there will be excessive clearance at the large end. Either situation can reduce the rigidity of the connection, and cause tool runout, which may show up on the workpiece as geometry and/or surface finish errors. Taper errors may also affect the amount of clearance between the flange on the tooling and the face of the spindle, which may create errors of axial positioning.

As the demands for precision machining and high speeds increase, manufacturing tolerances on spindle and toolholder tapers have gotten tighter. Nevertheless, both components are still subject to manufacturing inaccuracies and wear. In response, some companies with very high accuracy, quality, and throughput requirements—particularly in the aerospace and medical fields, and some automotive suppliers—regularly check the accuracy of toolholder tapers. This is usually done with differential air gaging, which combines the necessary high resolution and accuracy, with the speed, ease of use, and ruggedness required on the shop floor.

The most common type of air gage taper tooling has two pairs of jets on opposing air circuits, and is designed for a "jam fit" between the part and the tool. Jam-fit tooling does not measure part diameters, *per se*. Rather, it displays the diametrical difference at two points on the workpiece, as compared to the same two points on the master. If the difference at the large end of the taper is greater than the difference at the small end, as shown, the air pressure in circuit A will be lower than in circuit B: the gage will indicate this as negative taper. If the difference at B were greater than the difference at A, the gage would read positive taper. But because a differential air meter displays diametrical difference only, it will not display the part's diameter at either location. So while this type of air tooling provides a good indication of taper wear, and allows us to predict a loss of rigidity in the connection, it does not tell us anything about the tool's axial positioning accuracy.

For that, we need a "clearance" style air tool. The tool cavity is sized to accept the entire toolholder taper, while the toolholder's flange is referenced against the top surface of the tool. This makes it possible to measure diameters at known heights (in addition to the change in clearance, as in the jam-fit type). An additional set of jets may be added, as shown, to inspect for bell-mouth and barrel-shape—two more conditions that reduce the contact area between the toolholder and the spindle.

Given a basic understanding of how your air gage works, both types of tooling are easy to use. Mastering is simply a matter of inserting the taper master and adjusting the zero. Measuring is even easier: just insert the part and take the reading. Be careful when handling the heavy toolholders. Although the air tooling is very rugged, it's not totally impervious to damage.

## BEYOND THE HEIGHT GAGE AND SURFACE PLATE

***What can take low-volume, precision inspection to the next level?***

For many years now, the method of choice for low-volume, general purpose inspection has been surface plate work using test indicators and height gages. Recently, electronic height gages have made the layout inspection process a little more accurate. Speed of measurement has also improved, since electronic height gages give direct measurements and allow for storing data and programming repetitive measurement processes.

Are there even more advanced electronic height gages on the horizon that will allow us to achieve greater precision while still maintaining our ability to do a wide variety of measurement tasks? Probably not. The problem is not the height gage, but the reference surface it rests on.

No matter how precisely we build the height gage, the accuracy of the measurement is still dependent on the flatness of the surface plate. Surface plates probably cannot measure up to the increasing demands for higher tolerance measurements.

So where do we go from here? Consider the Universal Measurement Machine or

Universal Length Gage as a way to perform a wide variety of measurements and inspections with speed and improved accuracy. While there may be no all-purpose machine that can do everything, a universal length gage can do quite a lot. Applications include:

- Internal and external measurements of diameters and lengths (master rings and disc)
- Internal and external thread measurements
- Calibration inspection of mechanical indicators and gages (dial and digital indicators, LVDTs, test masters)
- Location of points, lines, holes and surfaces
- Internal and external tapers

Universal measurement machines were developed to speed up the inspection process and reduce the potential for measurement error. They differ from typical comparative style gaging because they have a much larger measuring range, but still can obtain resolution and accuracy approaching some comparators. In order to achieve high measurement performance, the machines have built-in reference standards either glass scales or an interferometer system.

When equipped with various contact accessories, universal measurement machines can easily be used to check length, diameter, pitch diameter, roundness, straightness, parallelism and taper. They will typically measure parts from 5 to 40 inches long, but machines are also available with even larger capacities.

These rugged looking systems are frequently referred to as "machines" because they are built according to the same design criteria as machine tools. Critically important measuring head and tail stock slide bearings are mounted on a strong and rigid base. The reference system is mounted as close as possible to the machine's line of measurement to avoid abbe errors. In addition, various computer techniques are used to map and correct slide errors; average multiple, lightning-fast measurements; and compensate for temperature variation. No, it's not a surface plate and height gage; but a machine that is extremely fast, versatile and very accurate. However, just like anything else, measurements made with the machine are only as good as the measurement process. Therefore, it is important to keep all the components of the process the same when setting (i.e., measuring the exact same location on the part, verifying gaging pressure, standardizing on a contact style, ensuring the utmost cleanliness of the part and contact, etc.). Machines do this with extensive computer-aided systems that help you set up a measurement process and then lead subsequent users through it the same way every time and, of course, capture and report measurement results and analyses.

The height gage and surface plate have been a mainstay for highly productive, low-part-volume general purpose measurements. The universal measuring machine incorporates the spirit of this process, while relying on a highly accurate internal reference to significantly improve measurement precision and repeatability. It is really an extension of the same line of thinking that has served manufacturers so well for over 100 years.

## DEEP THINKING
## About Depth Gages and Their Evolution

A depth gage is a very common hand tool used to inspect the depth of holes, slots, counterbores, recesses or the distance from one surface to another. They are especially common in the tool and die industry. Like other hand tools, they have undergone a gradual change from mechanical scales to digital wonders.

In the beginning a depth gage was simply a scale with a sliding head. The scale was set into the hole and the slide squared up with the reference surface. The depth of the hole was then read directly from the scale itself. This was a simple tool, but it did not absolve the operator of his responsibility to employ good judgment and proper technique.

To ensure consistent measurements with any kind of depth gage, it is important to adhere to some basic ground rules: Make sure the cross bar or reference head is clean, flat and free of nicks and burrs. Hold the manual gage flat and square to the reference surface. Any out of squareness of the head to the surface introduces error. So if you aren't careful, you may be measuring along the hypotenuse instead of the actual depth of the hole.

As tolerances increased, the depth scale gave way to the vernier depth gage. This type of gage took a little longer to read, but with some training and experience the users benefited from greatly improved resolution.

Both the scale and vernier type depth gages need to be set to zero. This is done by placing the measuring head on a flat surface, such as a surface plate, and moving the sliding arm or contact to the same surface. If the reading on the tool is not zero, it should be adjusted so that it is. Unfortunately, the sliding members of both the scale and vernier depth gage are quite large and are not suitable for measuring small holes (e.g., 1/4" or less).

Another improvement was the micrometer depth gage. It uses the barrel of the micrometer as the measuring leg and allows for entry into smaller holes. Micrometers provide for absolute rather than comparative gaging. Micrometer depth gages achieve very good resolution over their entire range; however, the range itself is limited. Therefore, for deep holes, an extension and a master are required. When using extension rods, always remember to add the length of the extension rod to the measurement value shown on the micrometer.

The digital caliper may also be used for making occasional depth measurements. Most incorporate a depth extension as a standard feature. The depth extension may be square or round, and the style of choice is determined by the hole size you need to measure. For the smallest of holes (less than 2 mm), round is the way to go. The only problem with using a caliper as a depth gage is that it's not what the gage is really designed to do. It is very difficult to align and hold the caliper square while making the depth check. The end of the caliper is just not designed for stability.

Of course, the fastest and most accurate tool for checking depth is the digital depth gage. Made in various sizes, digital depth gages may be fitted with a number reference for covering larger diameter spans. There are even extensions for spans up to 300 mm/12". Digital calipers are also self-supporting on the part and have sufficient width for good stability.

There are a number of different configurations for the actual depth contact. One version of these gages uses a small, fixed contact on the end of the slide to measure the depth. This is fine for general purpose applications where the opening is large. Another style uses a rod with a replaceable contact. This offers a lot more versatility, allowing the user to change contacts according to the surface that needs measuring.

The moral of this story: *There are many ways to check a depth dimension on a part. However, if speed and accuracy are important, use a tool that was designed for the purposeùtoday it's the digital depth gage.*

## 3, 2, 1, CONTACT MEASURING THICKNESS

Thickness is one of the most frequently measured dimensions, and also one that is very easy to understand. So you might think that someone would come up with a one-style-fits-all measurement approach good for just about every kind of thickness application. But it just ain't so. There are many approaches to measuring thickness, depending on the requirements of the part.

Some of the most common include micrometers, thickness gages, air thickness gages and motorized gages with many variations of each. They range in price and complexity from a few hundred dollars for a standard handheld tool to a few thousand dollars for ones that are custom-built for the application. One important consideration that makes each of these solutions different from the others is the way the gage makes contact with the part.

Whether it's the thickness of a piece of sheet metal, a silicon wafer, a latex glove or photographic film, we are usually talking about measuring the distance between two parallel surfaces. Accurately determining the length of a line that is perpendicular to two parallel surfaces has everything to do with how the gage makes contact with the part.

**Micrometer.** A handheld micrometer is a simple low-cost method for measuring the thickness of a piece of sheet metal, for example, which is relatively stiff and thick. It certainly provides a lot of measurement range. With flat and parallel contacts and constant gaging force applied with the friction or ratchet drive, the micrometer can self-align to the part for a fast and accurate reading. A potential problem with the self-aligning flat contacts of the micrometer is that they can bridge across and "average out" minute variations in thickness. So if higher resolution is required, you should look for a different approach.

**Thickness Gage.** The portable thickness gage raises the ante on resolution by combining a flat anvil-type reference surface on the bottom with a radiused (ball) measurement contact on top. Making a single point measurement eliminates the possibility of gage error that could be caused by faulty parallelism of the contacts. This would be a good gage for a narrow strip of photographic film where a spot check of thickness is required.

**Air Thickness Gage.** In some cases the part may be so susceptible to scratching or marring that any amount of gaging contact could destroy the part. An air thickness gaging system directs thin, precision-aligned, opposing streams to each side of the part which is held perpendicular to the air streams on a ground base. The gage measures back pressure on each of the air streams. Since the back pressure is directly proportional to the distance between the contact point and the nozzle, it is easy for the gage to automatically calculate thickness. This non-contact technique provides a means of sliding the part around for measuring thickness variation. The air provides enough cushion to help float the part as it is repositioned. The use of differential probing provides fast, accurate measurement regardless of where the part is positioned. Most importantly, the part is not damaged by the gage contacts.

**Custom Thickness Gage.** Many soft, compressible parts have rigid, standardized specifications for how they are to be measured. In such cases the design of custom gages will frequently take into consideration the size and shape of the contact along with the gaging pressure applied to the part. Usually the gaging pressure is defined as a dead load weight to assure constant force over the full range of measurement. However, with some compressible materials, such as paper or latex rubber, the amount of time that the load is applied to the part will also affect the reading from the gage. In these cases, the gage may incorporate a motorized measuring contact along with the cam actuated device to retract the contact after a specific period of time. This uniform load and dwell measurement prevents the parts from deforming and setting.

As you can see, the method of probe contact is a very helpful way to consider how to set up thickness gaging systems across a wide range of applications. Choosing the right approach can dramatically decrease the chance of inadvertently making a bad measurement.

## HAND TOOLS GET GEARED UP

Gears, while being a fundamental means of transferring motion and power, and simple in principle, are components with complex geometries which must be made with great precision to avoid premature component failure and high warranty costs. In recent years, tools and processes for measuring gears have come under great scrutiny by manufacturers, as well as reputable third parties such as NIST. In all the commotion, we sometimes forget that good solutions to seemingly complex measurement problems frequently involve the straightforward use of hand tools.

Depending on the manufacturing process, tolerance, and volume of gears produced, there are many different tools available for inspecting important characteristics. They range from simple but dedicated hand tools, to elaborate analytical testing equipment.

In high-volume industries, such as automotive, semi-automatic and automatic gages have proliferated to keep up with checks essential for dimensional, functional, and analytical process validation of gears. Hand tools, however, are both practical and fundamental, and play an important role in setting up these high-volume manufacturing and inspection processes, as well as in performing some types of in-process manufacturing checks. Compared to expensive CMMs, generative analytical testers, or gear roll testers, "off-the-shelf" hand tools have several important advantages: they cost much less, are accessible to more people, are portable, and they deliver results faster. Here are some basic tools that might provide some of the answers you need.

**Gear Size (DOB, DOP, or DOW** (Dimension Over Balls, Pins, or Wires)**).** Is the most frequently used method to monitor gear manufacturing processes for pre-sizing and/or tooling wear. Pre-sizing tests are used to control for additional processes such as shaving or grinding. Tool wear monitoring is one of the most common ways to track processes such as hobbing, shaping, broaching, powder metal, injection molding, and "near-net" gear forging. These tests are often used as a general indicator for specific undesirable size variations, including irregularities requiring other measurements or calculations.

**Gear Runout.** In the case of gears, runout is defined by the MAAG Gear Handbook as: "The maximum radial position change of a probe, measured in any transverse plane, with a probe placed in successive tooth spaces while the gear is rotating manually or automatically about its axis. The reading corresponds to the probe depth position perpendicular to the gear axis of rotation." Runout can often be used as a gross indicator for specific undesirable variations, including irregularities of the gear form (out of roundness), the mislocation of the teeth in respect to the gear axis (eccentricity), and variations of the tooth profile.

A very sound means for inspecting runout is to use a simple measurement stand with a single probe and a single ball whose diameter makes contact with the sides of the adjacent teeth at the area of the pitch circle.

**Tooth Thickness.** Another dimension important to a gear's function, easily checked with a hand tool, is the tooth thickness. Standard vernier calipers can be adapted to make this check easy for a direct measurement. The calipers have a small fixture that allows the top of the gear to be used as a reference point, so that the ball contacts of the tool align on either side of the tooth precisely at the pitch point (i.e., widest point on the tooth). Calculated measurements of tooth thickness can also be derived using measurements taken from gear size testing.

**Average Tooth Thickness.** There is still another way to skin the tooth thickness cat. It can also be derived from the measurement of the span chord over a number of gear teeth without the need for any specific reference point. This is great for in-process or on-the-machine testing. The measurement is made with a standard vernier caliper or micrometer adapted with disc-type contacts. The contacts are placed with one on the right and the other on the left flank of the most distant teeth in the span to be measured. Average tooth thickness is then determined using a standard table and formula which accounts for the number of teeth in the measured span, the number of teeth in the gear, and the pressure angle of the tooth (at the pitch circle). This method is not influenced by variations of runout of the outside diameter of the gear.

These examples of commonly used checks used in monitoring of gear production demonstrate how hand tools can provide simple solutions to seemingly complex gear measurement problems. To find out if there is a hand tool adaptable to your gear measurement requirements, contact a supplier with experience in this specialized field of measurement.

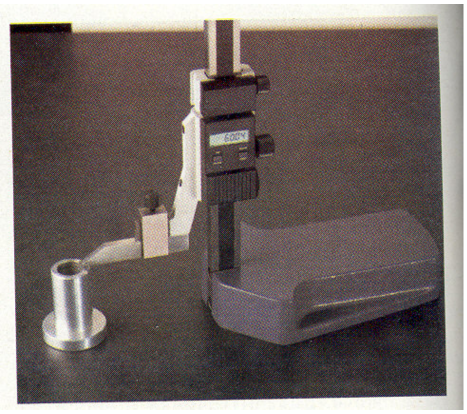
## THE "ISSUES" WITH HEIGHT GAGES

Don't tell any one, but there is something of a problem with height gages. The big issue that they have is what they measure, height. The larger the height gage, the bigger the potential problem.

It's not actually the height that is the problem. It's the relationship of a large height to the small base. Just like a lever—the longer the arm, the larger the multiplying factor—and with a height gage this is the problem. We are not only talking about the errors coming from the gage itself, but also errors in the setup. These get magnified and can potentially distort an otherwise carefully planned comparison.

A major error in the design of a basic height gage is taking a design that was meant to measure 12" and simply extending the post to measure 36", without changing the base design or the cross-area of the measuring post. What then naturally happens is that the gage will tend to wobble and flex. Although you may not be able to see the 0.001" wobble, it can become a significant part of the part tolerance and certainly influence the measurement.

A normal step in trying to increase the performance of the gage is to beef up the column in an attempt to reduce the flexure of the post. However, this only gets us part of the way to a better gage. For example, if a slight pressure is placed horizontally against the gage's measuring contact, the gage may slide along the table. If the same force is applied to the measuring contact when it is near its maximum upper position, this force will very likely cause the gage to tip over. What needs to be done is make the base longer and wider, and build in some mass. By decreasing the ratio of the post to the base there will be significant improvement in its performance.



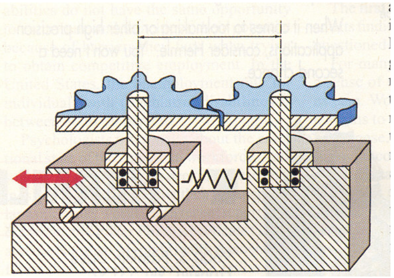
Besides its own personal issues, the height gage tends to keep company with tools having bad references. Most height gages are used with a surface plate. The surface plate provides the reference for the part and the height gage. Many surface plates are clean and well maintained. But there are those that may not be as clean as they look. A small metal chip or even a hair, while almost impossible to see, could throw off the measurement by 0.020" at a height of only 10".

Next to dirt, the actual surface of the granite surface plate will play a key role in the performance of the gage. Any slight imperfection between where the part and the gage are staged will get amplified the higher the measurement. Most surface plates have a flatness spec of 50µ". If the base is say 6" long, a 50µ" error would grow to more than 0.0003" in 36", and even worse if the plate is out of spec.

As a concerned parent to your height gage it's up to you to deal with its issues and choose who will be working with it. Look at the height gage to make sure it is beefed up for the job and check to make sure it has a precision surface to rest on.

## DFGT - DOUBLE FLANK GEAR TESTING (*NOT* Divorced Female from Georgia Tech)

Functional gear testing, also known as *total radial composite deviation*, is a method of looking at the total effect of gear errors. This test method simulates the conditions under which a set of gears is likely to operate as a result of the gears meshing together. The most common form of this test places the gears in a tight mesh, which produces contact on both flanks — thus the name of the gage to test this is aptly referred to as a *double flank gear tester*. The other less often used method of functional gear testing mounts the gears at their fixed operating distance. This method produces contact on a single flank of each of the meshing teeth. Believe it or not the name of this type of gage is a *single flank gear tester*.



Most indicator type gear testing (rolling) instruments are manually operated. These instruments are designed for use on the shop floor to monitor gear cutting quality. The use of these rolling gear testers is becoming more important as tolerances and machining requirements get tougher for metal and plastic gears.

Building a double flank gear tester is very similar to building any other type of comparative gage, except that with this type of comparator the master will be kept in the gage as part of the measuring loop. (See Fig. 1 for a typical rolling gear gage schematic.)

The work gear, or the gear being inspected, is mounted to a precision fixed arbor. A precision master gear is then mounted to an adjustable slide and brought into contact with the work gear. If variations between the work gear and the parameters of the master gear are apparent, rolling the two gears together in a tight mesh will result in a change in their center distance. This change reflects the total composite gear action that can be caused by improper gear profile, tooth thickness variations, gear runout or pitch errors. Surface finish errors, nicks or scratches in the gear teeth can also contribute to center distance variation.

The master gear used to inspect the work gear is just like any other comparative master in that it must be manufactured to a quality level substantially higher than that of the work gear. Just as there are level grades for gage blocks and master balls, likewise standards organizations have defined different quality levels for master gears. The master gear tolerances define the maximum variation for total and tooth-to-tooth errors.

Once the master and work gear are tightly meshed and running together, the composite variation needs to be recorded. The variation, or error, can be viewed by monitoring the position of the master gear with a comparative indicator of some type (mechanical or electric). The data can then be captured with a strip chart recorder or collected and analyzed by computer.

The most common method for evaluating the composite error is with the strip chart recorder. When the gage is run over a complete revolution of the work gear it's fairly easy to interpret of the total composite variation and the tooth-to-tooth composite variation. To make it even easier, some gages use tolerance lines on the strip chart, limit lights on the amplifier, or software limits to reduce the operator involvement in the measurement interpretation.

## AN INSIDE LOOK AT SPECIAL DIAMETERS

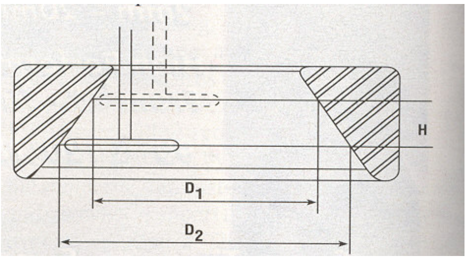
Sometimes we are faced with making critical inside diameter checks on parts that do not present themselves in a straightforward fashion. Usually these checks are on the inside of some type of bearing and they can be almost any size. Examples include measuring the diameter of an internal surface behind a shoulder, where the entry diameter is smaller than the diameter being measured; or measuring a ring groove in a bore, the pitch diameter of an internal thread, the effective diameter of a barrel roller bearing, or the included angle of a tapered bore.

Measuring this type of ID requires that the gage have some unique characteristics. These include the high repeatability of a comparative gage, long-range jaw retraction to allow entry into the part, and the ability to set the depth of the contact to make the measurement at the proper point.

Many people immediately think of a shallow bore gage for this type of application. As we have discussed in the past, this type of gage rests on the face of the part and measures the inside diameter at a certain depth. These are fairly accurate comparative gages that allow the depth of the contact to be set to a specific location. However, these gages are typically limited by the amount of travel found in the indicating device used for the readout. As a simple diameter gage they work well, but they do not meet the need of long range to get behind a shoulder, or to have the contact measure a groove diameter (Fig. 1).

Two types of gages do meet the needs of these applications: a gage very similar to a shallow, comparative bore gage, but with a long-range slide; and a long-range slide coupled with a high-resolution, long-range digital indicator.

The first example uses the precision slide purely as a transfer mechanism, or a way to retract the comparative indicator away from the surface to get past the obstruction. When released, it slides back against its stop and the comparative indicator does its thing. This sounds like a simple solution until one considers the mechanics involved. The contact has to be long enough to get down and around the smaller diameter. This is where the design of the slide and contact become critical. If the slide has any looseness in it, it will cause the gage to be unrepeatable. Or, if the contacts are too flimsy, they will bend and twist and become sensitive to placement and gaging pressure. Either of these design flaws in the precision slide can make even the best comparative indicator look bad.



A better way of achieving the same result is to use a long-range digital indicator as part of the measuring frame. This has the benefit of actually referencing the measurement based on the accuracy built into the gage's own long-range slide. Of course, the contacts must be designed to handle the depth and gaging pressures, but the beauty of this type of gage is that its long range offers the ability to measure any number of depths within its range. So, besides measuring a depth at a particular location, it can measure two diameters at different depths, thus becoming a taper gage measuring the included angle of the tapered bore (Fig. 2).

The combination of the long-range, high-resolution digital indicator on a soundly designed mechanical frame can provide a universal ID (or OD) gage that has endless applications for those hard-to-reach inside measurement applications.

## HOLES BIG ENOUGH TO FALL INTO

Maybe you're not in Texas, but suddenly you find yourself faced with a huge measurement requirement. You've been given the task of checking some large diameters… Not your 6" variety, I mean those large enough to drive a herd of cows through. You know, the 12", 36" or even the 80" variety.

Don't go for the tequila yet. There are lots of choices available to meet this challenge, which boils down to selecting the right tool for the application. The first step is to look at the part print, determine the measurement tolerances, and see if there are any callouts for out-of-round conditions. Those two pieces of information will lead you to the best tool for the job.

If the tolerance is loose—in the 0.01 ins—then a digital or vernier caliper-style gage will provide a good fast check of the part diameter. Just make sure the jaws are square to the part and placed to find the major diameter. On the larger diameters, this could even be a two-person operation.

An inside micrometer is another alternative. Special kits make it possible to assemble a series of calibrated extension rods to span any diameter. Because this is a true point-to-point measuring system, the diameter has to be found by rocking the gage both axially and radially. On a large bore, this may require one operator holding the reference side of the gage in place while the second operator "searches" for the maximum diameter.

Tighter tolerances call for different types of gages. Some adjustable bore gages can get to these larger sizes. They deliver improved accuracy and repeatability because they: 1) are adjusted to a specific (in this case large) size range; 2) provide comparative measurements using a master; and 3) are often equipped with a centralizer which makes it easy to "search" for the diameter. Pair this gage with a good digital indicator which includes a dynamic function to store the maximum size, and you have a great tool for fast, repetitive readings.

Gages with beams that have reference and sensing contacts mounted on either end are another comparative tool. In addition to satisfying large diameter measurement requirements for tolerances within the 0.001 ins, beam type gages have standard rest pad and contact combinations that allow measurement of shallow bores and thin wall parts, as well as grooves and other features machined within the bore. You can even build up the gage to get around a central hub.

When the blueprint requires you to check not only the diameter but out-of-roundness as well, the bar has been raised. The gages mentioned above can still be used, but the process may involve making five or ten measurements on the part, recording the results, and calculating out-of-roundness according to a formula. Not only is this approach time consuming, it also magnifies operator influences on the result because so many measurements are required.

An advanced concept can be brought into play here: the better the gage is staged, the better the result of the measurement. That's why the shallow bore gage with its two references is better than the gages that just have one reference. By the same thought process, another reference point will result in even further improvement. Let's take the same shallow bore gage, but this time we will use it with a staging post that centralizes both the part and the gage. The operator only has to apply a little force to make sure the reference contact is against the part, and the central post takes care of finding the maximum diameter without having to rock the part back and forth. Now it's a breeze to inspect for out-of-round conditions.

Just rotate the gage, keeping a little force applied to the reference contact and watch the swing of the needle, looking for the min and max values. Watching the needle, you can visually inspect for the Total Indicator Reading (TIR) or out-of-roundness variation. Add a memory to the indicator, or an amplifier to store discreet points, and you can automatically calculate the average roundness.

By building on solid measurement concepts, staging the gage and the part, and eliminating operator influences, you can easily reduce your Texas-style large diameter measurement problems down to the size of Rhode Island.

## ECONOMICAL CHOICE OF BORE GAGE DEPENDS UPON YOUR APPLICATION

Indicating bore gages come in two basic varieties: adjustable-capacity gages with interchangeable contacts or extensions; and fixed-size gages with plug-type bodies. While indicating plug gages can measure closer tolerances with higher repeatability than adjustable ones, these are only two of several factors to consider when selecting a bore gage. A wrong decision can mean unnecessary expense, low throughput, and even inaccurate data.

There is still a place in many shops for adjustable bore gages. Where tolerances are medium to broad, or production runs are low or involve many different bore sizes to be measured, adjustable gages can be a bargain. Their range is typically two to three times greater than that of plug gages (0.010" vs. 0.003" - 0.006"), so they are more practical to use with broader tolerances. Because an adjustable gage can measure a range of hole sizes, some shops can get away with just three units, with capacities of 0.500" - 1.00", 1.00" - 2.00", and 2.00" - 8.00". With indicating plug gages, on the other hand, a separate size plug is required for every different bore size to be measured. The two types of gages are comparable in price (generally $500 - $600), but for a broad-tolerance operation, the smaller number of adjustable gages required will create a substantial savings. When you figure in the cost of masters, the savings can be multiplied.

For large-ID applications, adjustable bore gages are again the economical choice. Over about 4.5 inches, most plug-type gages are "specials" and, consequently, expensive (likewise for masters). Adjustable gages and masters are available from stock with capacities up to 24 inches.

The greatest benefit of fixed-size plug gages is the elimination of "rocking" to center the gage in the bore. The self-centering plug gage virtually eliminates operator influences and required very little training. Rocking an adjustable gage is a refined skill that must be learned and performed conscientiously (Figure 1 and 2). A poorly trained operator, or one who is tired or hurried, is likely to produce incorrect measurements. Adjustable gages are also more subject to intentional operator influences, also known as the "close-enough syndrome."

The elimination of rocking speeds measurement taking considerably. Mastering is likewise simplified and accelerated. In any production run where volumes are high and/or tolerances are tight, plug gages create time savings that quickly amortize their higher purchase price.

I am not endorsing indicating plug gages over adjustable ones, but the fact is, they offer more benefits overall. Plug gages have larger bearing surfaces which make them less subject to wear. They are capable of better repeatability and discrimination. And they are the only logical choice for use with an electronic data collection system. It is nearly impossible to hold an adjustable gage steady on the true diameter of the bore, and at the same time, push a button to record the reading.

To summarize: Use adjustable bore gages where production runs are low and/or tolerances are medium to broad. Use self-centering plug-type gages where quantities are high and/or tolerances are medium to tight.

## IMPROVING HEIGHT GAGE RESULTS

As with any measurement, the quality of the result depends on the measurement instrument and the care with which the operator handles the measurement procedure. Many gages are designed to make this as easy as possible. A snap gage, for example, has the reference anvil, frame and measuring instrument built it. The same is true with a bench stand. To obtain a good measurement, all the operator really has to do is correctly apply the gage to the part.

With an electronic height gage, this is not quite the case. Electronic height gages are not as self-contained as other gages. They have the precision scale and the sensing probe, but no integral reference, which is the most critical part. Most electronic height gages are used on a granite surface plate and the plate provides the reference for both the height gage and the part that is being measured. The quality of this base plate directly influences the measuring result. Thus, it is important to keep the plate free from dust, chips and dirt.

Most height gages are direct reading instruments that generally operate in ranges up to 36 inches. As such, they are especially susceptible to variations in temperature. Since the body heat of the operator (98.6 ° F) is clearly above the room temperature (68 ° F), any heat conveyed to elements of the measuring circuit (base plate, test piece, height measuring instrument, stylus) can cause local heat expansion and induce measurement errors. Operators should be very careful in observing the following rules:

- Avoid touching the test piece with your bare hands directly before the measurement. Use gloves.
- Do not touch other elements of the measuring circuit.
- Only touch the height gage at points provided for this purpose: handles are usually provided to move the gage or engage the air bearings for positioning.
- Avoid drafts.
- Avoid direct sunlight on the instrument, test piece, or base plate.
- Do not set up the measuring station in proximity to radiators or in the path of air ducts.
- Do not check test pieces that were transported through very hot/cold rooms shortly before measurement.
- For high precision measurements, put the test piece on the base plate and let it adjust to ambient temperature (approx. ¼ to 8 hours, depending on the size of the part).

Once the measuring loop is verified, there are two other critical references that need to be established. The first is the zero-reference for the measuring system. With automated height gages, this is done automatically whenever the gage is turned on. In a manually driven gage, the gage must be zeroed on the granite plate before it can be used. With a motor driven unit, the gage will automatically move down to touch the surface to set its reference point. It's not a bad practice to initiate this zeroing routine a second time, just to make sure that no dirt or other anomaly has introduced an incorrect reference. Since setting this reference is critical to all the measurements you will make, it is certainly worth the time and effort.

The other important reference is the correction for probe ball diameter. If a height gage is to be used only for length measurements taken with the probe moving down, then probe diameter is not important. The contact point of the probe will be the same as in zeroing. But, if grooves, diameters, or the hole locations are being measured, or if any measurements are taken with the probe moving upwards, then the probe ball diameter must be known and taken into account.

Ball diameter is specified for the probe, of course, but there is always some degree of variation. Actual ball diameter should be added to any dimension that is probed in the upward direction.

On height gages that have even the most basic electronic control this dimension can be measured as part of a set-up routine and is automatically included in all measurements. The automated process uses a fixture provided with the gage, or the test can be simulated with a couple of gage blocks. The fixture sets up a plane that is measured by the gage from both directions. The gage then looks at the difference between the two measurements and calculates this as the ball diameter.

The same gage block check can be done by hand on purely manual machines or the ball diameter may be measured off-line with a micrometer. Just as with setting the zero reference, this check should be repeated a number of times. A lot of gages will provide this repeat check automatically and reject the ball diameter reference if it does not repeat to within a preset limit.

Failing to recheck for ball diameter can be a deadly pitfall when a probe tip is changed. Going from a 10- to a 5-mm ball tip would be disastrous if not recalculated.

## AIR GAGING STYROFOAM

Over the years we have discussed a great many successful uses of air gages in this column. We have seen it used to measure diameters, tapers, straightness, and even little bitty holes. Air gaging has always proven to be an excellent choice for fast, easy-to-use and reliable, high performance dimensional gaging. But did you ever think it could be used to check those Styrofoam end caps that secure your new stereo system in its shipping container? Well, it can, and it does it very well.

Styrofoam, or expanded polystyrene (EPS), is a basic term for styrene polymers that can be expanded into a multitude of different products. EPS has been available for more than 50 years and proven in numerous packaging applications. It is ideal for packaging and shipping applications because of it's strength, light weight, cushioning characteristics, dimensional stability, and the fact that it is thermal and moisture-resistant.

EPS is supplied to molders in the form of polystyrene beads that are loaded with a blowing agent, usually pentane, and other agents that give the beads the ability to expand and be molded into low-density foam products. In the end, EPS is 90% air – which accounts for its light weight. By varying the mixture of chemicals and the heating process, the foam characteristics can be changed to vary the density and create the best mix for the specific packaging requirement.

So what does this have to do with air gaging? Because the density can be varied to change the characteristics of the material, the end product then has to be checked to make sure it will perform under load. You have probably noticed differences in some of the Styrofoam products that came with your DVD player or new computer: some are rock hard, while others may be a little "crumbly" and break apart easily. What is at work here is the bonding agent in the foam. Regardless of the desired density, if the bonding agent has been used successfully, the beads will all be held very tightly together. If not, they will tend to break apart – not only in your hand, but during the transport of your precious new toy. Bonding removes air between the beads and seals the matrix.

This is where the air gaging comes in. The less air between the beads, the stronger the bond. The more air, the weaker the bond. And if there is air between the beads, there is also a path for air to flow through. By applying pressurized air to the Styrofoam, we can monitor the flow of air through the material. It's like using air to measure little bitty holes, but in this case we are measuring a lot of itty-bitty holes. Just as we used the air gage as a flow meter for small holes, we can do the same for this material.

In the application, an open-air probe is pushed into the Styrofoam part. A stop collar on the end of the probe limits the probe travel into the part and also acts to seal off any air escaping from the hole. If the bonding of the beads is good, there will be virtually no place for the air to go, which presents high back pressure to the air gage. If the bonding is not so good, there will be gaps between the beads allowing the air to flow through, resulting in less back pressure.

Just as with previous flow gage examples, we need a set of reference standards to set up the low end of acceptability. The gage is then set up with these standards to create the limits. Now it's pretty easy for the operator to use: he brings a part to the gage, sticks in the air probe and observes the scale. Limit lights can also be used to set the acceptable limits.

Another characteristic of EPS is how well it flows through the mold and matches up to the molding surface. If the flow is correct, it will follow exactly the surface of the mold. If the mold has a flat surface, the part will be flat. Should the flow not be correct, the beads will not completely form the surface and the end result would be a slightly bumpy surface that could easily break off and get into the shipment. Again, air gaging can be used to check this by manufacturing an open-air jet probe with a large flat surface, which is laid on the surface of the part. If the surface is smooth, the probe will seal nicely with the part. If the process was not quite right, gaps will exist, allowing air to escape. Both cases represent changes in back pressure that the gage can measure and display.

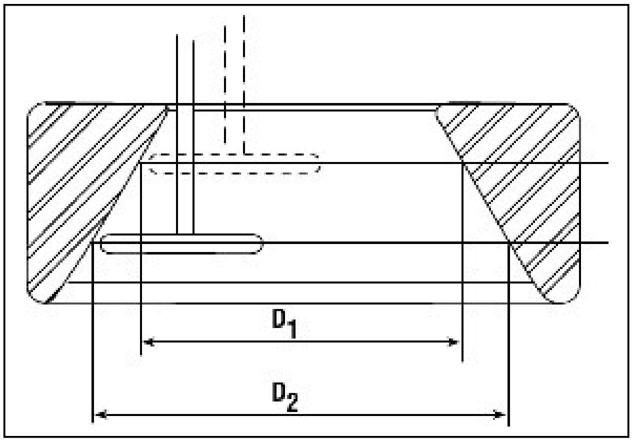
What is next for air gaging? Well, let's see…how about tapioca pudding?

## AN INSIDE LOOK AT SPECIAL DIAMETERS

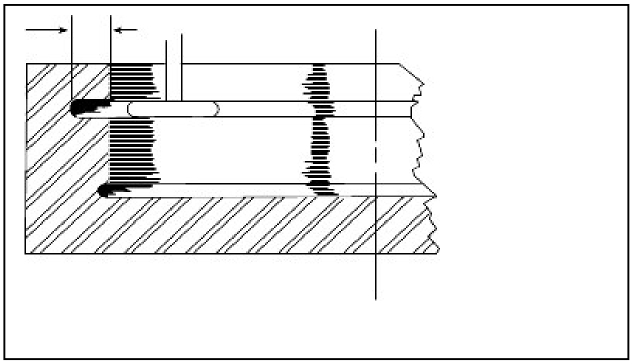
Sometimes we are faced with making critical inside diameter checks on parts that do not present themselves in a straightforward fashion. Usually these checks are on the inside of some type of bearing and they can be almost any size. Examples include measuring the diameter of an internal surface behind a shoulder, where the entry diameter is smaller than the diameter being measured; or measuring a ring groove in a bore, the pitch diameter of an internal thread, the effective diameter of a barrel roller bearing, or the included angle of a tapered bore.

Measuring this type of ID requires that the gage have some unique characteristics. These include the high repeatability of a comparative gage, long-range jaw retraction to allow entry into the part, and the ability to set the depth of the contact to make the measurement at the proper point.

Many people think of a shallow bore gage for this type of application. As we have discussed in the past, this type of gage rests on the face of the part and measures the inside diameter at a certain depth. These are fairly accurate comparative gages that allow the depth of the contact to be set to a specific location. However, these gages are typically limited by the amount of travel found in the indicating device used for the readout. As a simple diameter gage they work well, but they do not meet the need of long range to get behind a shoulder, or to have the contact measure a groove diameter (Fig.1).

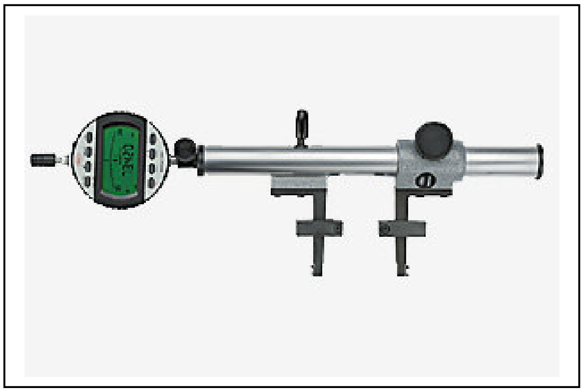


**(Fig.1)**



**(Fig. 2)**

Two types of gages do meet the needs of these applications: a gage very similar to a shallow, comparative bore gage, but with a long-range slide; and a long-range slide coupled with a high-resolution, long range digital indicator.



The first example uses the precision slide purely as a transfer mechanism, or a way to retract the comparative indicator away from the surface to get past the obstruction. When released, it slides back against its stop and the comparative indicator does its thing. This sounds like a simple solution until one considers the mechanics involved. The contact has to be long enough to get down and around the smaller diameter. This is where the design of the slide and contact become critical. If the slide has any looseness in it, it will cause the gage to be unrepeatable. Or, if the contacts are too flimsy, they will bend and twist and become sensitive to placement and gaging pressure. Either of these design flaws in the precision slide can make even the best comparative indicator look bad.

A better way of achieving the same result is to use a long-range digital indicator as part of the measuring frame. This has the benefit of actually referencing the measurement based on the accuracy built into the gages own long range slide. Of course, the contacts must be designed to handle the depth and gaging pressures, but the beauty of this type of gage is that its long range offers the ability to measure any number of depths within its range. So, besides measuring a depth at a particular location, it can measure two diameters at different depths, thus becoming a taper gage measuring the included angle of the tapered bore (Fig. 2)

The combination of the long-range, high resolution digital indicator on a soundly designed mechanical frame can provide a universal ID (or OD) gage that has endless applications for those hard-to-reach inside measurement applications.