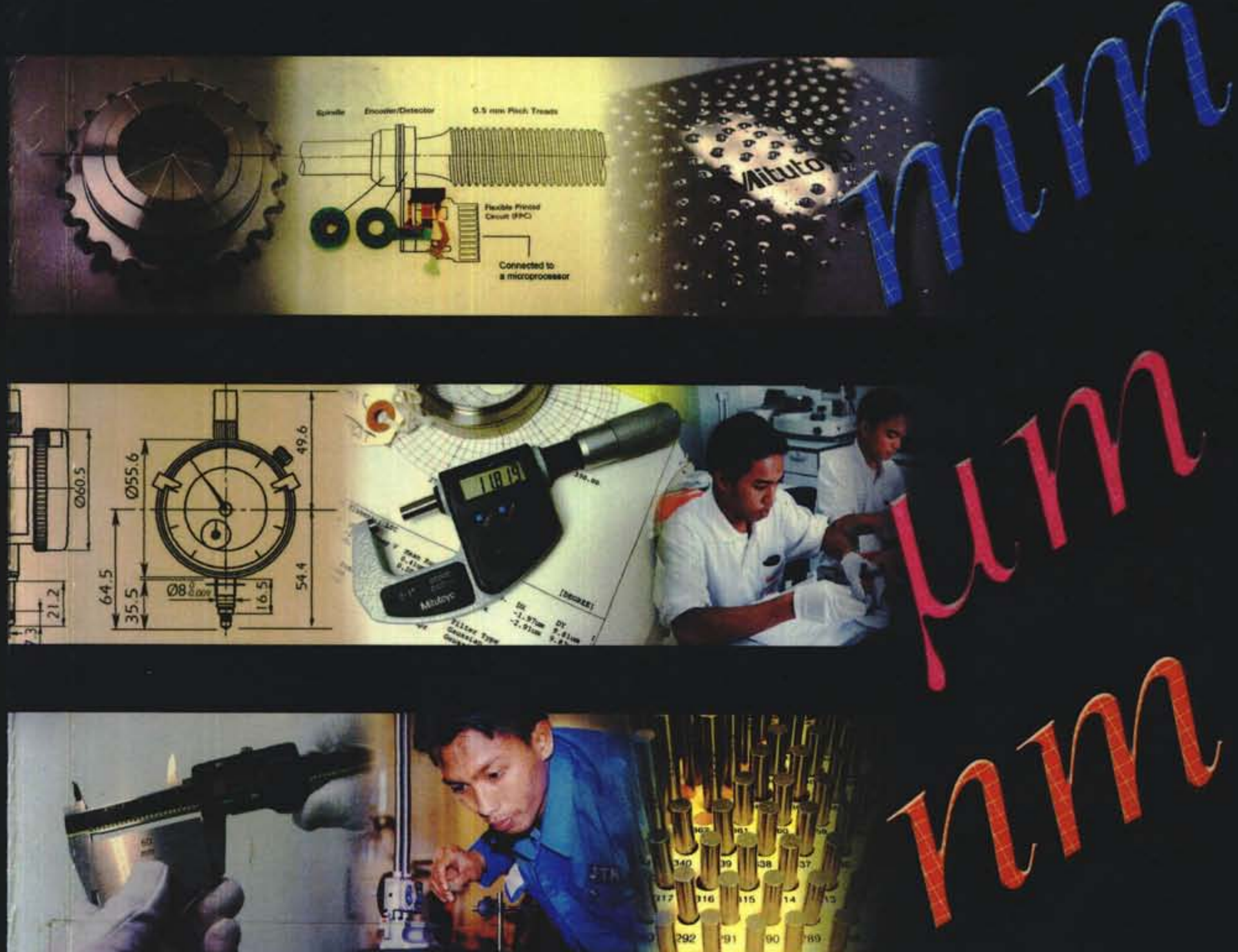
Mitutoyo

METROLOGY HANDBOOK

The Science of Measurement



Metrology Handbook

The Science of Measurement

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Asian Version
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To those who measure, measure most precisely

Mitutoyo
Institute of Metrology

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Preface

The ability to measure workpieces precisely is an essential component in the quest for quality improvement. This is more important today than any other period, as tolerances are much tighter than they used to be. Dr. W Edwards Deming taught us "continuous improvement": How to continuously improve "quality" (trustworthiness) of data is one of the central issues in this Metrology Handbook. Unreliable measured data will yield unreliable quality.

Having taught tens of thousands of engineers in the metalworking field, we recognised the need for a comprehensive handbook that can give step-by-step instruction to many questions raised during the Mitutoyo metrology seminars.

How to measure precisely is taught on the job. This time-honoured method certainly works but it would work even better, we feel, if a handbook was there to refer to. By learning how to measure correctly, bias in measured data will be minimised. "Continuous reduction in variability" — a key concept in quality improvement — will be achieved by minimising bias and variance in data.

This Handbook is written in both inch and metric values. In converting inch to metric and vice versa, rounded conversions are used for the sake of simplicity. For example, 1 micrometre (1 µm = 0.001mm) is rounded to 40 microinches (40 µin or .000040 in) whereas the correct answer should be .00003937 in. The most significant equation between inch and metric is: 1 in = 25.4 mm (exact). In this text, it is rounded to 25 mm when appropriate. Below is a short list of rounded conversions.

Note: µ, one of the most frequently used Greek symbols in the industry, is often referred to as "micron", to denote one thousandth of a millimetre. In this Handbook, it will be used in "µm" and "µin" for microinch.

There is more than one way to express inch. "IN" is allowed on the predominantly metric engineering drawings where inch values must be inserted. The more common inch abbreviation (") is not used in this text. Instead, inch is shown as "in" without a zero before the decimal point (e.g. .004 in) in accordance with the current ASME Y14.5M-1994 standard. In comparison, a zero is added before the decimal point for metric dimensions below 1 mm (e.g. 0.5 mm) as specified in the same standard.

This is the Asian Edition, based on the American Handbook Version 1.3.

Rounded Conversions

Inch to Metric (Rounded)		Metric to Inch (Rounded)	
.000001 in	25 nm	1 µm	.000040 in
.000002 in	50 nm	50 µm	.002 in
.0002 in	5 µm	100 µm	.004 in
.001 in	25 µm	100 mm	4 in
1 in	25 mm	600 mm	24 in

Note:
1 µm = 0.001 mm and 1 in = 25.4 mm exact

PART I

Fundamentals

PART I:
FUNDAMENTALS

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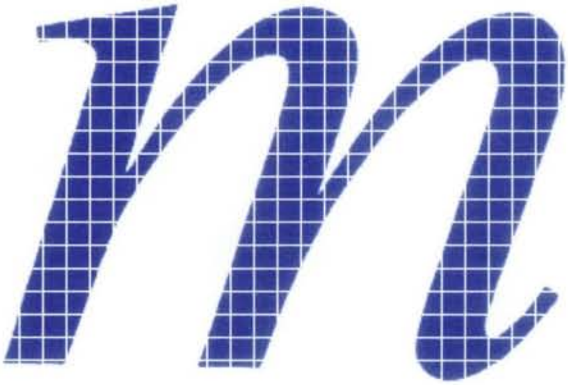
- Summary

Chapter 1 Introduction

"À TOUS LES TEMPS À TOUS LES PEUPLES"



Metre – The Universal Standard of Length

By the time of the French Revolution (1789) - one of the most turbulent and chaotic periods in recent history - it became clear to many of the intellectuals in France that the unit of length must be derived from a physical constant whose value stays unchanged.

Historically, the unit of length was derived from a human limb. Cubit (the length from the bent elbow to the tip of the middle finger) in ancient Egypt was the standard unit centuries ago, not to mention the Fathom (outstretched arms), and foot, which are still used today. Those lengths worked well until the arrival of modern times since they were available to everyone, rich and poor.

When the metre was finally defined, after a seven year journey by two astronomers who measured the distance from Dunkerque to Barcelona (see page 16) by triangulation, the modern unit of length was found to be, quite ironically, only twice longer than the ancient Egyptian cubit. Metre or yard, the standard of length produced by man reflects his scale. The issue however is not the length itself, but rather the universal acceptance.

In today's language, it would be a mission statement when they proclaimed "À TOUS LES TEMPS, À TOUS LES PEUPLES" (for all time, for all people). Yet, the advantages of the English units should not be underestimated. "Fractions" such as 1/4 and 1/8 are useful units, so are 1 inch and its multiple 12 inches. There is more than a fair chance for inch to stay. To be able to speak French (metric) and English (inch) is a distinct advantage.

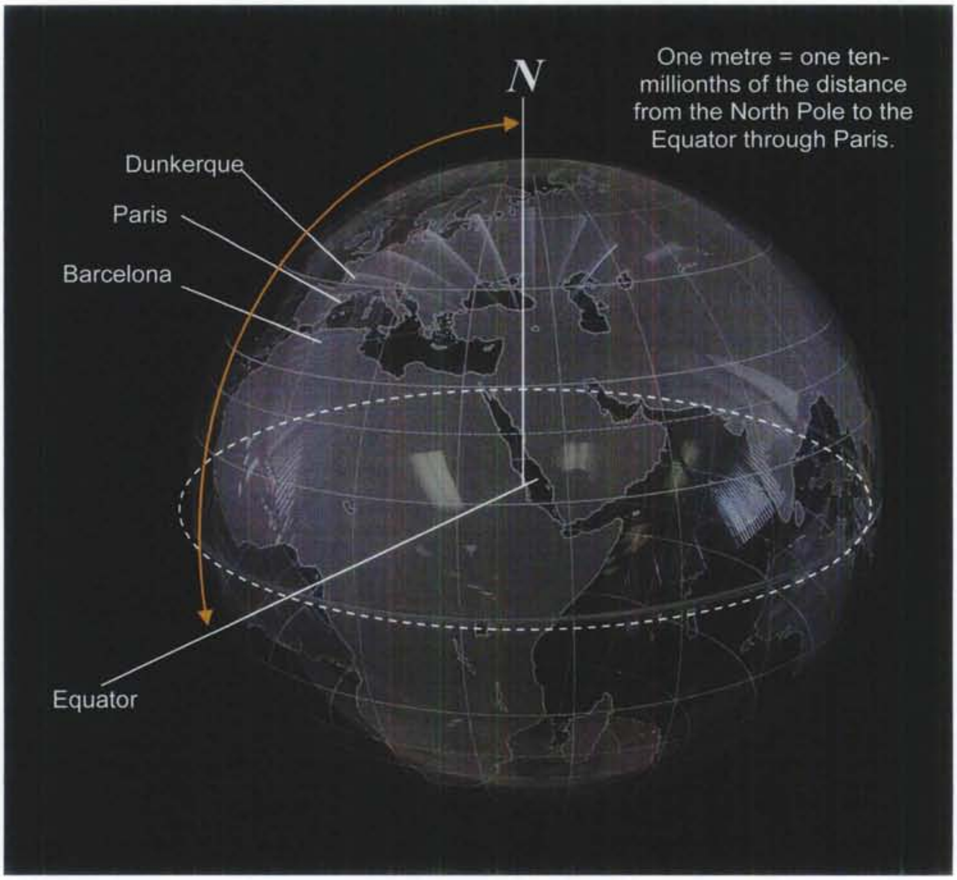
In Search of a Constant

The Awakening

During the eighteenth century, the centre stage for mathematics, geometry, philosophy, and other scientific inquiries moved from England into France after the passing of Isaac Newton (1642-1727). Long before the French Revolution French intellectuals and scientists started to propose a new set of standard units based on a physical constant.

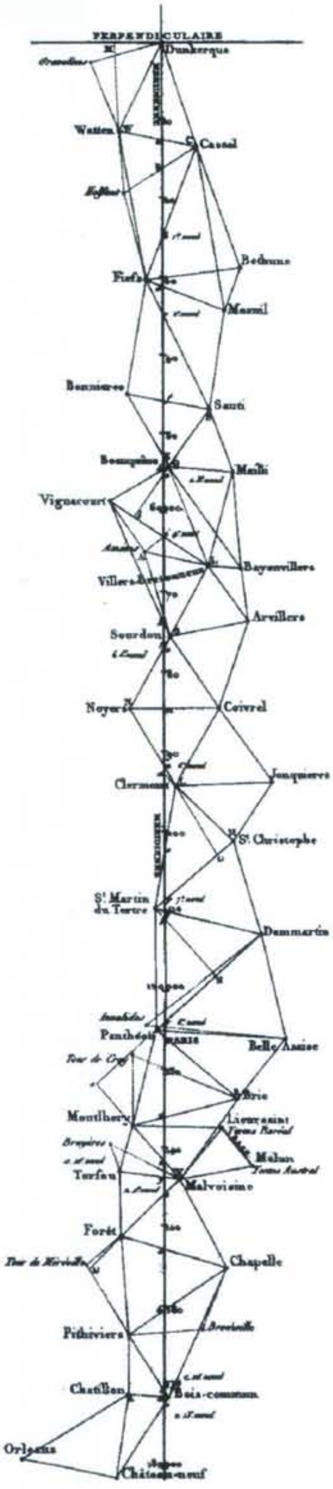
One proposal was to use the length of a pendulum as a standard. However, pendulums were affected by gravity, and thus its length could differ from one place to another. Therefore the proposal to take pendulum length as a new standard unit was rejected, although 45° parallel was suggested for its standard location. Instead, there rose a concept of scaling the quadrant of earth from the North Pole to the Equator through Paris as illustrated below. This extraordinary proposal in astronomical scale was approved by the French Science Academy, and the members suggested a name for it: Metre.

The name "Metre" (Mètre) chosen by the Academy was from the Greek "Metron" and also "Metrum" in Latin for "measure". To determine this length, one quadrant of the Earth's surface was to be measured. Without standing on the North Pole or on the equatorial line, they managed to calculate the distance by taking a small sample segment from Dunkerque, which is on the northernmost point due directly north of Paris, to Barcelona. Both points are located on sea level and the distance between them is the longest land-based meridian through Paris.



Once this was surveyed, the data was interpolated to calculate the quadrant of the earth circumference, called the Great Arc. This was then subdivided into 10,000,000 equal parts, one part of which was the new unit of length. The interpolated distance was adjusted to compensate for the slightly ellipsoidal earth. Thus the definition of metre was created. It was based on the decimal system.

Whether the public would accept it or not was another matter, for Napoleon brought back the old units, leaving the metre on the brink of extinction.



The Seven-Year Journey

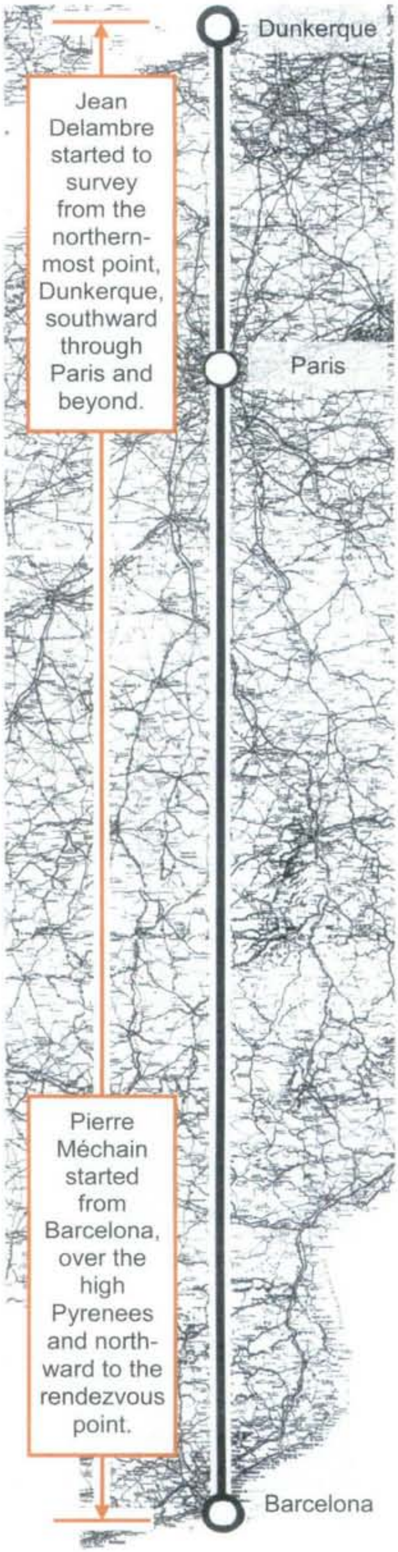
When the astronomer Jean Delambre (1749-1822) stood on the shores of Dunkerque, he must have faced south. Beyond the horizon and beyond Paris, his minds' eye may have seen a small town called Rodez. Likewise, when the other astronomer, Pierre Méchain (1744-1804), stood by the Mediterranean Sea on the opposite end, he must have visualised his final destination across the Pyrenees.

The two astronomers, Delambre and Méchain, left Paris in 1792. One went to the north and the other to the south. Their assignment was to measure the distance between the two sea-level points by triangulation. Delambre, who headed north, may have picked the easier part, for although the distance was much longer the terrain was flat. In contrast, the land mass given to Méchain included the snow-capped Pyrenees, the natural barrier separating France from Spain. In their capable hands were the angle-measuring equipment made by Lenoir called the "Borda Repeating Circle". One unit was based on the customary 360° while the other was engraved in the new decimal system: 400° - a concept then embraced by many.

When Delambre started his journey southward from the northernmost point, the Bastille had already fallen (1789) and the Revolution broke out in earnest. The epicentre of the French Revolution, Paris, could not be avoided because it was located on the direct line of longitude, then the meridian zero degree for the French. (It was only later that it was moved by only 2 degrees to Greenwich) When Delambre reached Paris, he found it in disorder. He was subsequently arrested and had his surveying equipment seized. By then he had only measured no more than a quarter of the total distance required.

Mapmaker, Cassinis

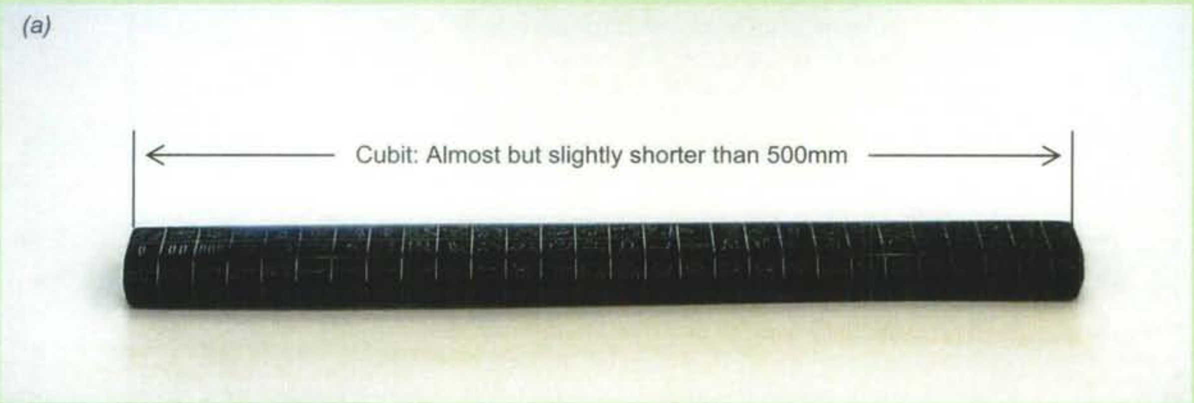
Their epic journeys took seven years and ended in 1799. One cannot help wondering why this journey took place. The answer lay in the fact that this had been done before by Giovanni Demenico Cassinis, professor at Bologna and astronomer to the Pope. A modern map of France was produced during the period of Louis XIV. Two astronomers were required to validate the distance measured earlier by Cassinis. This must have tipped the scale in favour of validating Cassinis' survey over the pendulum method. Once re-measured, the quadrant known as the Great Arc could be estimated by interpolation.

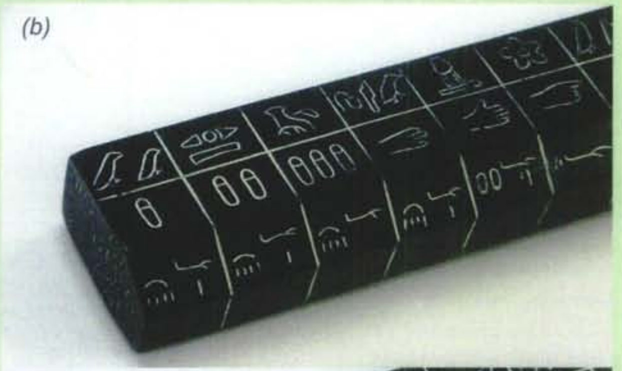


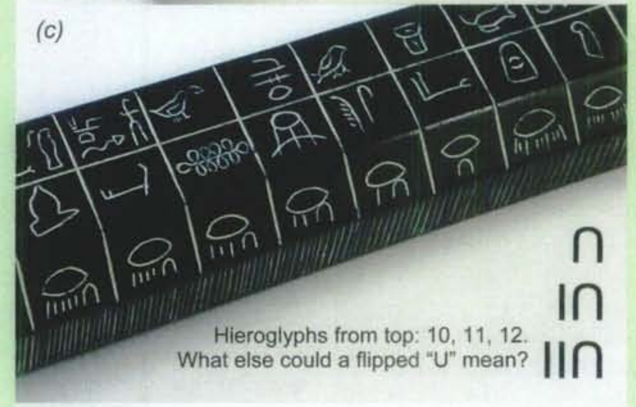
Jean Delambre started to survey from the northern-most point, Dunkerque, southward through Paris and beyond.

Pierre Méchain started from Barcelona, over the high Pyrenees and northward to the rendezvous point.

Birth of a Standard – The Egyptian Cubit







Hieroglyphs from top: 10, 11, 12.
What else could a flipped "U" mean?

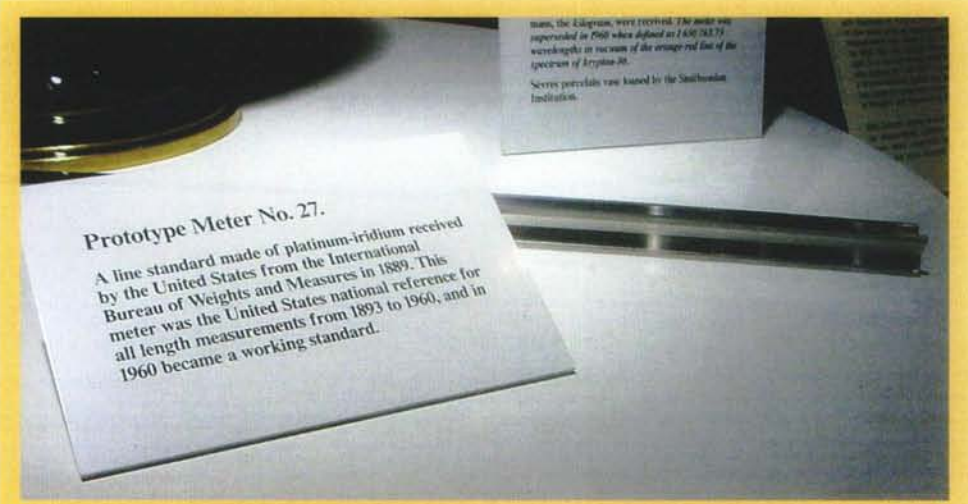
A common unit of length called the "fathom" is the length of two outstretched arms, used for measuring the depth of water. A standard unit called "shaku", which originated in ancient China and migrated into Japan, was the length of an outstretched palm from the edge of the thumb to the tip of the middle finger. For all length standards in the past, it was only natural to use a part of the body, as everyone was roughly the same size and it was convenient to perform measurements using them.

The ancient "Cubit" was the distance between the bent elbow and the tip of the middle finger of a powerful Pharaoh. Even without being able to read hieroglyphics, it is clear that certain characters and symbols engraved represent units, as the close-ups *(b)*, *(c)* and *(d)* suggest. By dividing a cubit (which is approximately 500 mm long) into 28 parts, one part becomes approximately 18 mm, a known unit with a distinct symbol. This in turn was subdivided into two, three, four, or sixteen, which appears to be the smallest graduation.

Many centuries later, a pair of astronomers embarked on an epic journey, seeking to survey the land to estimate the circumference of the earth to declare a new standard. It was ironic to find that when the modern metre was defined, the new unit of length turned out only to be about twice longer than the ancient Cubit. Had they subdivided the Great Arc into twenty million parts instead of ten, the Cubit could have been today's standard of length.

Artefact Standard of the United States

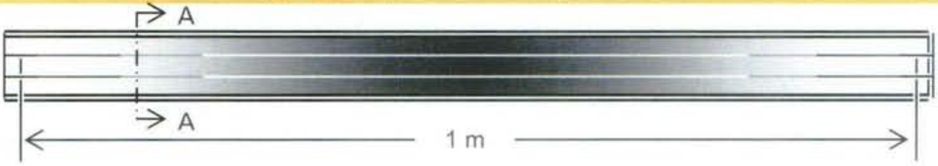
Like gold, platinum is among the rarest of all metals and is less abundant than silver by a factor of 10. The difference between platinum and silver can be recognised even by the untrained eye: platinum is exceptionally white and beautiful to watch.



Prototype Meter No. 27.

A line standard made of platinum-iridium received by the United States from the International Bureau of Weights and Measures in 1889. This meter was the United States national reference for all length measurements from 1893 to 1960, and in 1960 became a working standard.

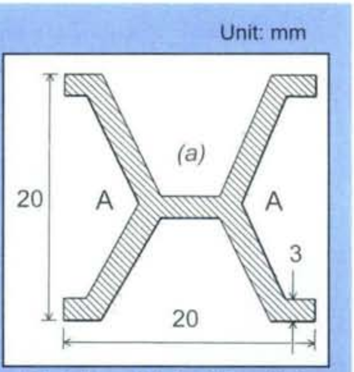
Prototype Metre (a.k.a. Metre Bar) is a line standard



Platinum was discovered accidentally by the Spanish Conquistadores in search of gold in South America. Like gold, platinum does not corrode or tarnish and retains its original beauty. Unlike gold, the discovery of platinum was delayed because of its higher melting point. According to a recent study, half of platinum produced is consumed by the catalytic converter. According one old story, Spain wanted to monopolise platinum trade, but a small quantity was successfully "smuggled" into England where iridium was separated. Iridium is a by-product of platinum, and is known to be the hardest of all metals. To choose platinum as a length standard was a correct choice. Nevertheless it cannot maintain the same length forever. Platinum is a dense precious metal and is nearly twice more expensive than gold in today's' market.

The metre bar cross section reveals how thin the metal is (3 mm), yet this configuration allows it to offer maximum rigidity, particularly where key two lines are etched *(a)*.

Horizontal plane *(a)* is located in the centre and is guarded from potential twist. This classic design is repeatedly applied in other measuring gauges and standards.

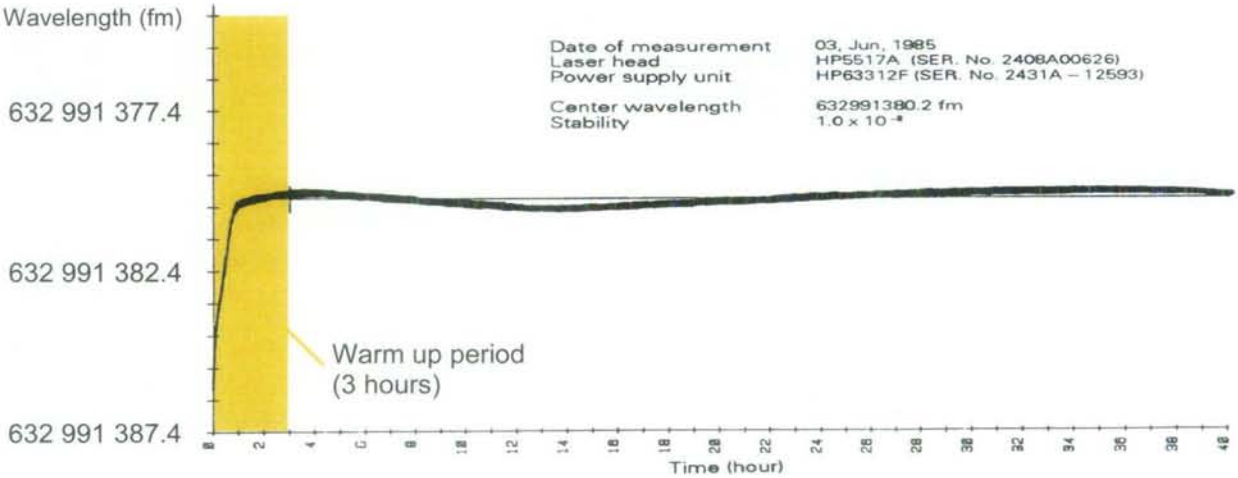


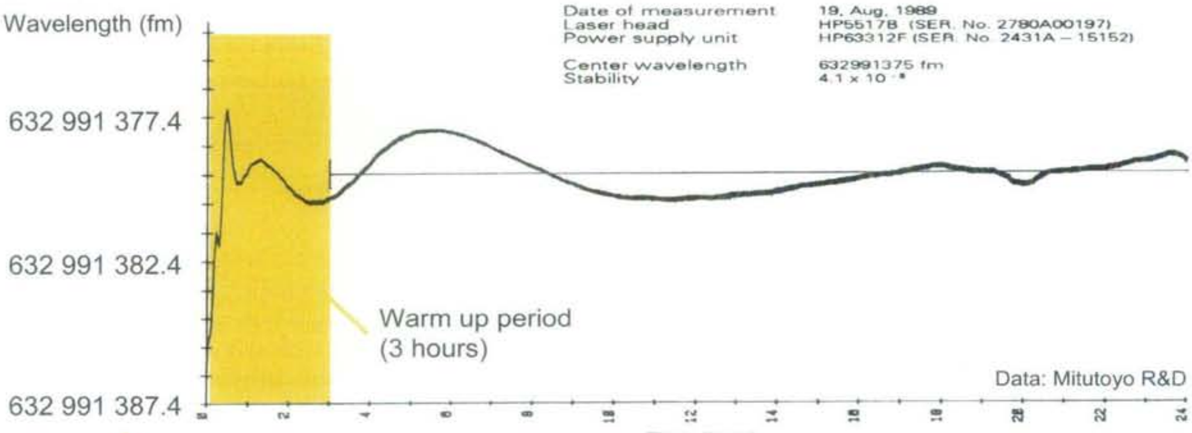
Prototype Metre View A-A

The cross-sectional view of the metre bar resembles letter "H" or "X" as shown here. In this configuration, the least amount of the precious metal needs to be used whilst keeping it structurally solid. In 1960 this metre bar, the length standard of the nation, was reclassified by NIST as a working standard.

For a brief period of time after 1960, the wavelength of Krypton-86 replaced metre bar, but it was soon replaced again by the newly invented Helium-Neon laser. Had the laser emerged much earlier, Krypton-86 would not have been a standard of length.

Helium-Neon Laser Interferometer (HP 5517)





0.000 632 991 387 4 mm

Nanometre Picometre Femtometre

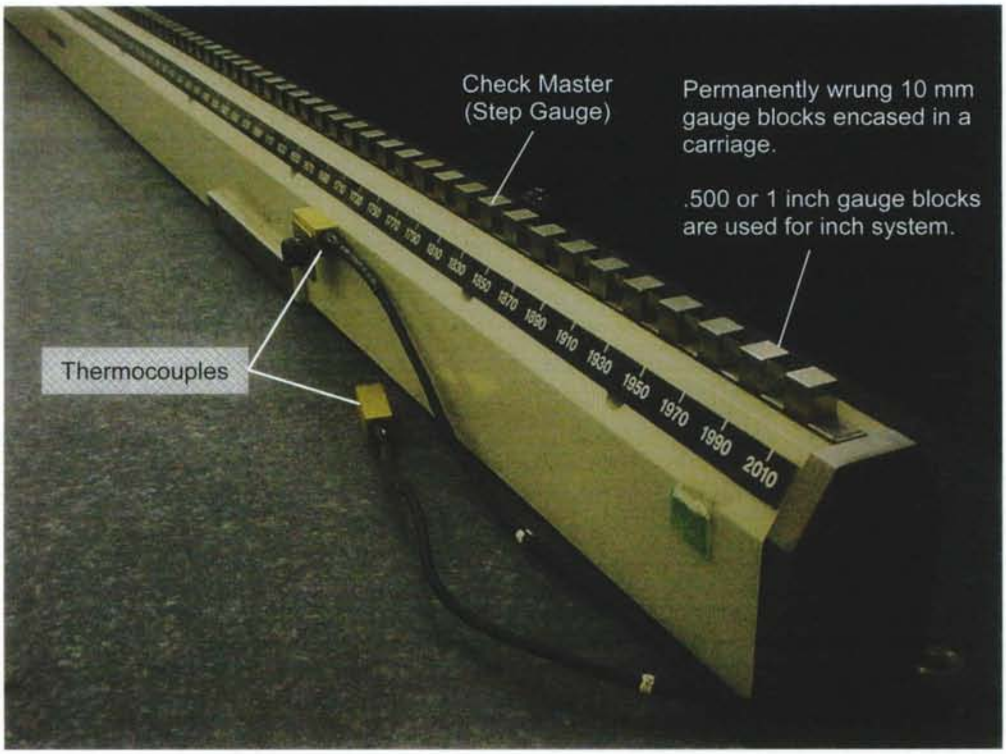
All Helium-Neon laser wavelengths produced by different interferometers increase in length over time, some as much as five femtometres (5 fm) in five years, while other models remained relatively stable. 5 fm is five thousandths of a picometre and five millionths of a nanometre.

Test Unit #1	632 991 382 fm
Test Unit #2	632 991 412 fm
Test Unit #3	632 991 371 fm
Test Unit #4	632 991 379 fm
Test Unit #5	632 991 331 fm
Test Unit #6	632 991 388 fm

It is the wavelength of the Helium-Neon (He-Ne) laser from which the most precise length is derived today. The ability to measure wavelengths a million times below micrometre level, therefore, becomes a critical and essential issue to the determination of length. The heart of the He-Ne laser is its tube from where monochromatic and coherent red light emerges. A technician who calibrated more than 400 Hewlett-Packard He-Ne laser interferometers states that the HP second series, Model 5518, is more stable than the original 5517 Series. As shown in the accompanying table at left, each unit produces very slightly different wavelengths.

The Long-range Length Standard

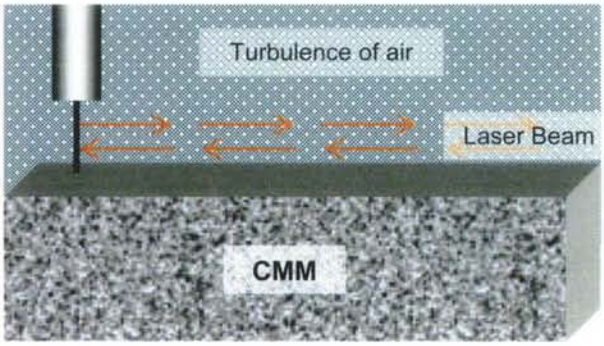
The artefact length standard such as this Check Master shown here made of steel gauge blocks would be ideal for CMM calibration. However, the trouble with this type of standard is that it cannot be much longer than 2 metres. This particular unit is 2010 mm in length; it is already extremely long and unwieldy. As a result, any lengths greater than this standard would best be represented by other means, such as by the wavelength of a laser.



Extensive studies into the laser indicate that the wavelength of the Helium-Neon laser expands over time, but only 5 femtometres in 5 years or so. For all practical purposes, it is safe to say that the wavelength stays "constant". The extraordinary discovery into the world of femtometres (millionths of a micron) is only possible under controlled conditions. What if the laser interferometer is placed in a "normal" shop environment?

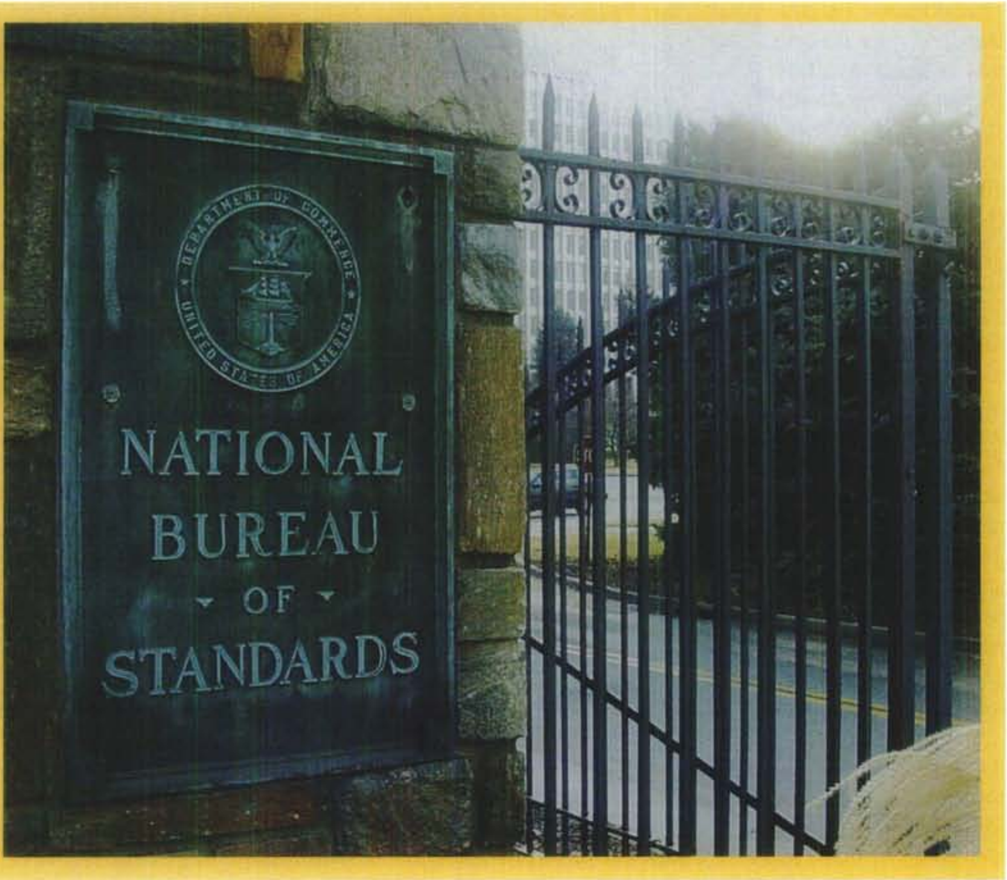
Because laser interferometers are much lighter and more portable than the Check Master, they are used to calibrate long-range CMMs. Laser accuracy in an air-tight room under 20±0.5°C appears to be 5 µm (.0002 in) per 1 m (40 in) according to one study.

Coefficient of Thermal Expansion	
Steel Gauge Block	11.5 ppm/°C
Ceramic Gauge Block	9.2 ppm/°C
Granite Plate	6.3 ppm/°C



Environmental disturbances such as movement of air can affect the laser path. However, when carefully calibrated, an accuracy of 1 µm (.000040 in) per 1 metre is attainable in 2 sigma levels, and may be the best-case accuracy of the laser. The presence of turbulent air particles appears to influence the outcome the most.

National Institute of Standards and Technology (NIST)



Currently located in Gathersburg, MD., this gate still holds its original name from when it was first established in 1901.

Behind it is the main administration building.

Established by an act of Congress in 1901, National Bureau of Standards (NBS) was located in downtown Washington DC. It was renamed National Institute of Standards and Technology (NIST) under the Bush (Senior) Administration in 1988 and was assigned new responsibilities. Unlike other agencies typically located within the I-495 loop, the NIST is a unique non-regulatory government agency under the Dept. of Commerce and its primary mission is to work with U.S. industries. It is at the NIST where calibration of gauge blocks and other highest-level of calibrations are performed. In its "Mission Statement", NIST pledges to promote the growth of the economy by working with various industries to develop and apply technologies, measurements, and standards. NIST carries out its mission through a portfolio of the following four major programs:

1: Measurement and Standard Laboratories
Provides technical leadership for the nation's measurements and standards and assures the availability of essential reference materials

2: Manufacturing Extension Partnership
Strengthens the global competitiveness of smaller U.S.-based manufacturing firms by assisting in the adoption of advanced technologies.

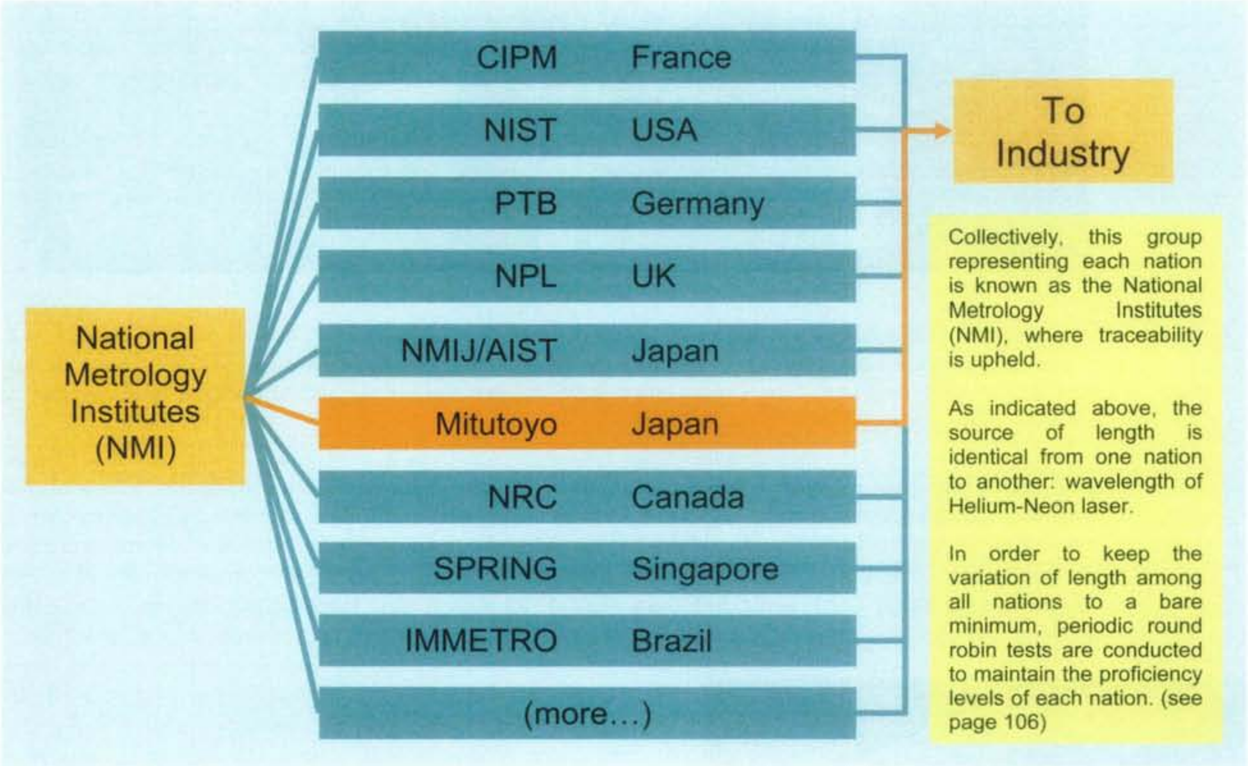
3: Advanced Technical Program
Stimulates U.S. economic growth by developing high-risk technologies through industry-driven cost-shared partnership

4: Notional Quality Program
Enhances U.S. competitiveness, quality, and productivity, and manages the Malcolm Baldridge National Quality Award.

Traceability of Length on the Global Scale

The most precise length created today is through the calibrated and stabilised wavelength of laser. To date, Mitutoyo has recalibrated over 400 Hewlett-Packard Helium-Neon (He-Ne) laser interferometers. Each unit calibrated by qualified technicians produces an absolute master of length, from which national-level laboratories collectively called NMI (for National Metrology Institute such as NIST). The list below is a partial list of the National Metrology Institutes around the world.

The standard of metre is based on the iodine-stabilised Helium-Neon laser, having a wavelength of 633 nanometres. As a result of an extensive investigation into the wavelength, it became clear to the R&D engineers of Mitutoyo that the wavelength expands a minute amount over time which is scientifically significant over a long period. For all practical purposes, however, it is correct to assume that the wavelength stays constant. The discovery of movement in the domain of femtometres (a millionth of a micron) was presented in a technical paper at the NCSL (National Council of Standards Laboratories) meeting in Atlanta, GA.



Collectively, this group representing each nation is known as the National Metrology Institutes (NMI), where traceability is upheld.

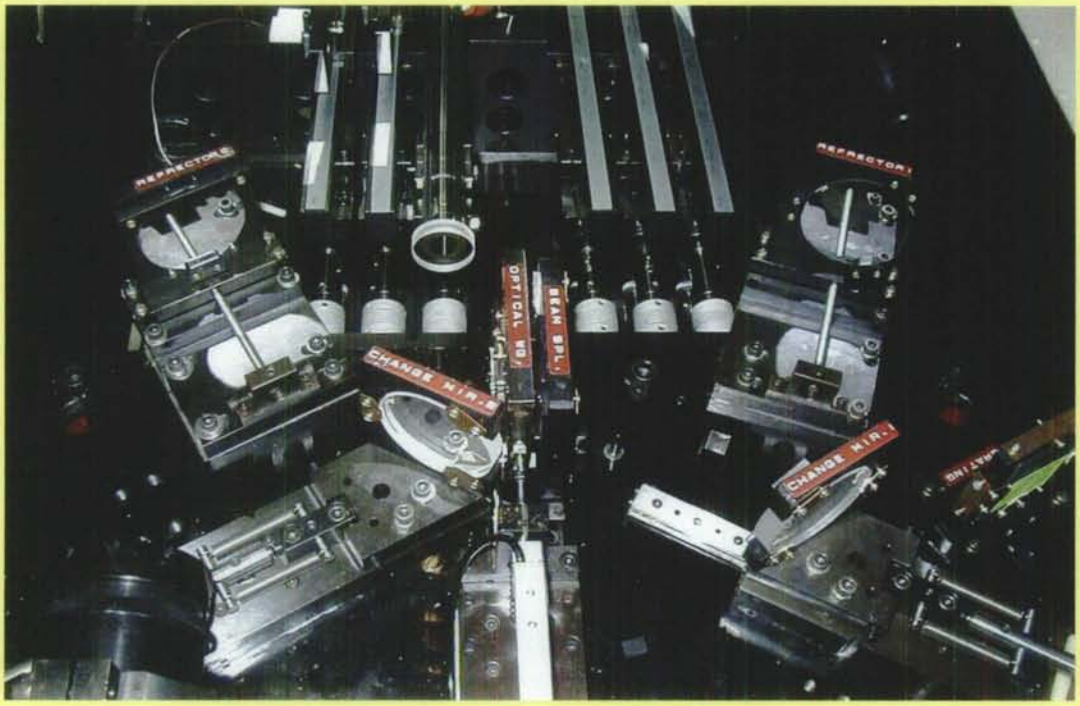
As indicated above, the source of length is identical from one nation to another: wavelength of Helium-Neon laser.

In order to keep the variation of length among all nations to a bare minimum, periodic round robin tests are conducted to maintain the proficiency levels of each nation. (see page 106)

CIPM stands for the International Committee of Weights and Measures. In defining the metre, it decided not to specify any particular wavelength on which is was based on, but made a change in the measurement hierarchy in 1983. Prior to this, the standard was based on the wavelength of Krypton-86. The change was to define the metre in terms of speed of light in vacuum at exactly 299,792,458 m/s and make length a derived unit. In actual practice, the time-of-flight method is impractical for most applications and therefore the metre is most commonly established using a known wavelength of light such as Helium-Neon laser.

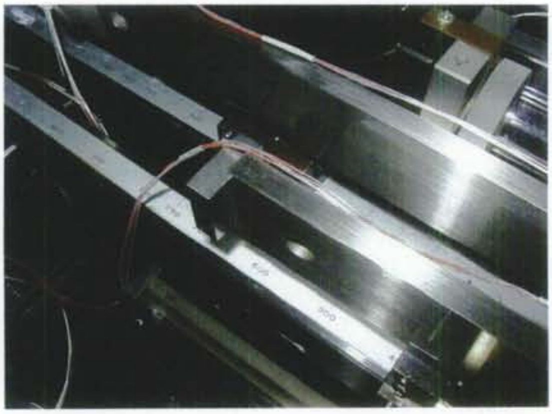
Absolute Length Defined by Light

Mitutoyo Gauge Block Plant



The metre is defined today in terms of speed of light in vacuum which travels at 299,792,458 m/s, where one metre is the inverse of this equation (metre per second - second is SI). While the definition is scientific in nature, any organisation with proper equipment and knowledge will be able to produce standard lengths.

In place of the speed of light which is impractical for establishing lengths, the Helium-Neon Laser with 633 nanometre wavelength has been chosen. Typically, the iodine-stabilised red laser beam is employed for establishing the length produced under the most carefully controlled temperature and environmental conditions. This red laser is basically the same laser beam commonly found at any supermarket counter for reading barcodes. The difference is that those lasers emerge from a tiny diode, while the one in this application is energised in the traditional method from a long laser tube.



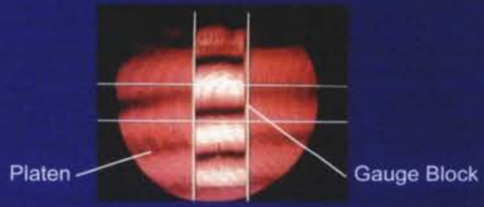
The laser interferometer, first successfully marketed by Hewlett-Packard in the 1960s, is a preferred source in the area of metrology. Since its first model, HP has gone through a series of improvements in design. As a result, current models appear to be more stable than earlier ones. The wavelength of the laser remains generally "constant" although R&D engineers at Mitutoyo have detected extremely small changes in the little known domain of femtometres. By and large for all practical purposes, it is not incorrect to say that generally, the wavelength of the 633 nm He-Ne laser remains constant over time. It is against this wavelength that gauge blocks are compared.

End Standards

Mitutoyo Gauge Block Interferometer (GBI)

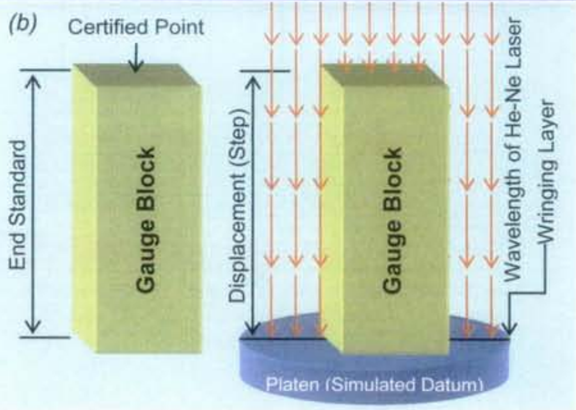
All Mitutoyo Gauge Blocks are compared against the wavelength of the Helium-Neon laser. Because the calibrated light moves from top to bottom in the controlled chamber, gauge blocks are placed atop a flat disc called Platen. Skilled technicians read the wavelength and determine the actual length of gauge blocks under observation.

(a)



Close up of Screen:
To be able to read fringe pattern (dark bands) top and bottom together, platen must be present.

(b)



Gauge blocks fall into a category called the "end standards" as opposed to the "line standards" such as glass scales. An end standard is, as its name suggests, a standard from one end to the opposing end. Despite popular belief, when gauge blocks are compared against the wavelength of light, they are wrung first to a flat surface called platen. See illustration at left *(b)*. In this configuration, the distance measured is from the top surface of the gauge block to the top surface of the platen, or a step from the bottom to the top surface.

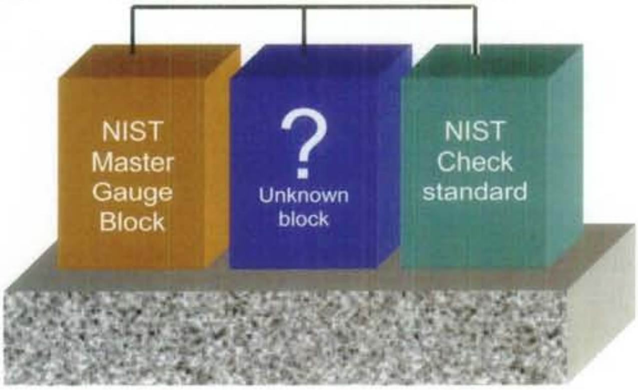
It is in this manner many gauge blocks will be used on a granite surface plate. In many applications the gauge blocks are employed to produce a step just as drawing *(b)* suggests. The platen or the top surface of the granite surface plate serves as a datum plane.

Thus, the most precise length is determined by the wavelength of light at all National Metrology Institutes including NIST.

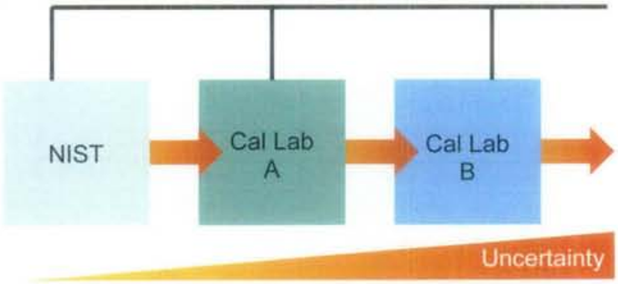
These Gauge Blocks made by Mitutoyo serve as standards for the United States at NIST

Courtesy NIST

(a) "Check standard" checks NIST masters



(b) An unbroken chain of comparisons



Each laboratory will produce measurement uncertainty. Additional reference: A2LA Guide for the Estimation of the Uncertainty of Dimensional Calibration and Testing Results (July 2002)

Most calibration laboratories calibrate unknown gauge blocks against traceable known blocks, where the unknowns are the blocks submitted by the user and knowns are the master blocks made traceable to NIST. In a normal calibration only two parties, known and unknown, will be involved. At NIST and many other primary laboratories, they go one step further to safeguard the system as illustrated in *(a)* where three blocks will be involved in calibration.

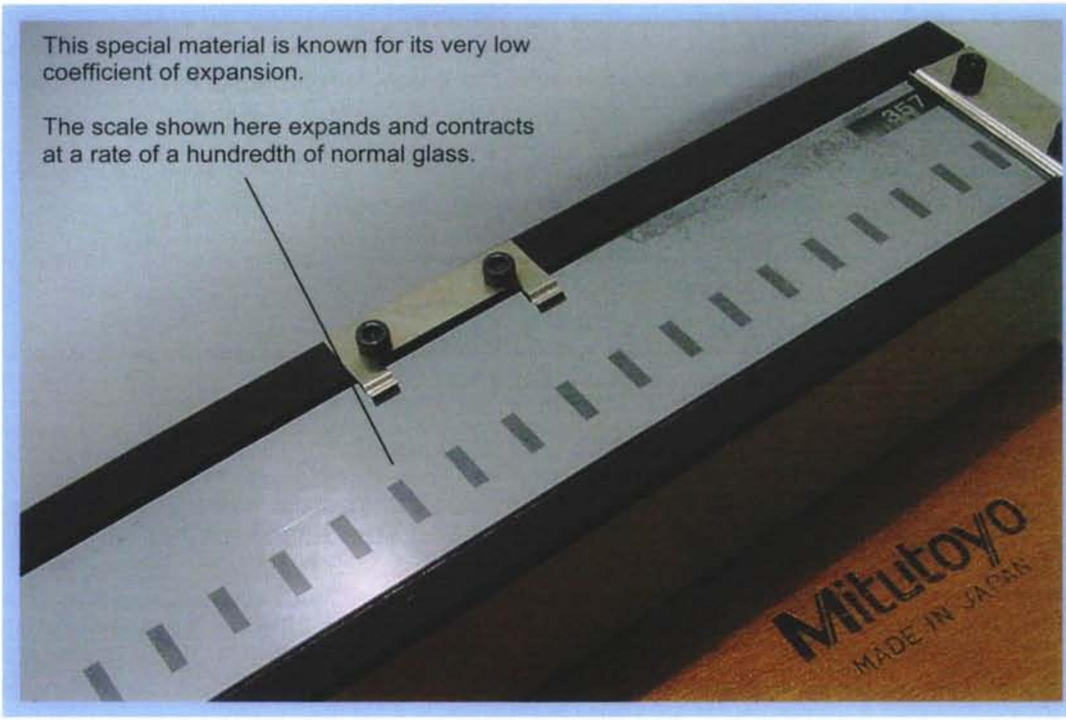
The presence of a NIST check standard is the safety net in this comparison. A number of gauge blocks at NIST are designated as check standards, such as those provided by Mitutoyo above.

No measurement can be perfect, even though capturing the "true" value is the aim of all calibration technicians. Even at NIST, measurements yield small uncertainty values due to many factors such as temperature and other variable elements. Uncertainty levels at NIST for gauge blocks are as follows: (k=2 is roughly 95% confidence level and are indicated in all uncertainty statements)

NIST Uncertainty Value Examples	
Below 25mm (1 in)	25 nm (.000001 in)
100mm (4 in)	50 nm (.000002 in)

Stated in expanded uncertainty k=2

Line Standards



This special material is known for its very low coefficient of expansion.

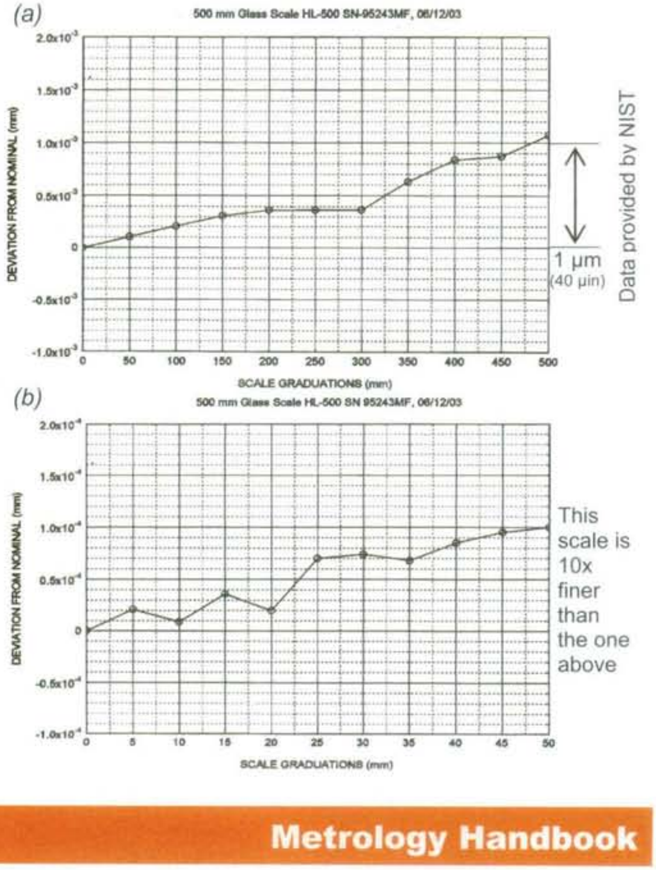
The scale shown here expands and contracts at a rate of a hundredth of normal glass.

Line Standard for calibrating Optical Measuring Instruments

There are two basic standards in length. They are: (1) End Standards, covered on the preceding pages, (2) Line Standards, briefly covered on this page.

This artefact made of a very low-expansion material called Zerodur (0.05 ppm/°C) was calibrated at the Nano-Scale Metrology Group at NIST. Their test equipment was the Line Scale Interferometer, which uses a stabilised Helium-Neon laser corrected for temperature, humidity and atmospheric pressure. While this line standard was under calibration, the environmental chamber and the artefact temperature were held within ±0.005°C of 20°C. The NIST uncertainty for 0 to 50 mm was 0.008 µm (8 nanometres) and for 0 to 5 mm was 0.005 µm (5 nanometres).

For the linear distances displayed and projected on the screen (e.g. Optical Comparators), or generated through a CCD camera, magnification may reach well over 1000 times. At this scale, the level of accuracy is critical. The reported NIST uncertainty values, 8 nm for 50 mm *(a)* and 5 nm for 5 mm *(b)*, are among the smallest ever recorded.



Data provided by NIST

This scale is 10x finer than the one above

Summary

The artefact length standard (i.e. Prototype Metre No. 27) at NIST is no longer the standard of length in the U.S. The advent of the Helium-Neon (He-Ne) laser, one of the most significant inventions in the twentieth century, has changed the hierarchy of length. It is the wavelength of this laser that now defines standard length.

The old MIL-STD-45662A "Calibration Systems Requirements" published in 1960 and remained effective for more than 30 years states as follows on the subject of traceability:

> Traceability: The ability to relate individual measurement results through an unbroken chain of calibrations to one or more of the following:
>
> - U.S. national standards maintained by the U.S. National Bureau of Standards (then NBS now NIST) and the U.S. Naval Observatory;
> - Fundamental or natural physical constants with values assigned or accepted by the U.S. NBS;

Three more methods by which traceability can be established are also mentioned. In short, if one can prove his or her gauge block is traceable to the NIST, then traceability has been established.

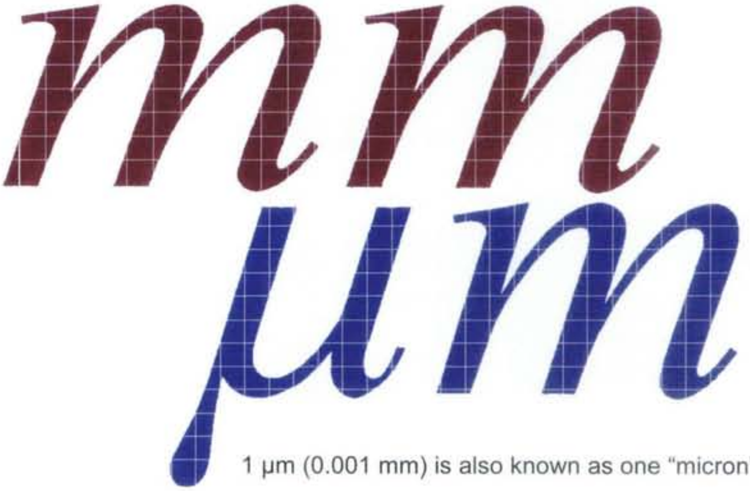
Much stronger than this case is the traceability to fundamental or natural physical constants. The Helium-Neon laser is such a constant. How constants are measured by Mitutoyo R&D engineers to the level of femtometres (see page 20). Certainly, the wavelength changes slightly over time, but so small in magnitude that it is generally considered to be constant. The traceability to a physical constant such as a laser is one level more credible than the traceability to NIST, because NIST is producing its length from the same He-Ne laser under controlled conditions.

For those who interested in finding more about how two French astronomers triangulated the distance from Dunkerque to Barcelona, read '*The Measure of All Things*' by Ken Alder (Free Press ISBN 0-7432-1675-X). The hard cover was published in 2003. In this book, the author revisits all the triangulation points used by the two astronomers.

How accurately each national-level laboratory can measure length is checked by a system called Round Robin Testing (proficiency test). The result of such tests can be analysed by a chart called a Youden Plot. All participants in the test must come within a circle of measurement uncertainty (see page 106). Commercial laboratories are strongly suggested to participate in such test by the American Association for Laboratory Accreditation (A2LA).

Chapter 2

Units on Engineering Drawings



1 µm (0.001 mm) is also known as one "micron"

All engineering drawings in metric are specified in millimetres: 22, 3050, 0.4, etc. Rarely are four-digit millimetres entered on the blueprints unless the specifications are for car or truck chassis. There is just one exception to this rule: Surface Roughness. The values indicated on the prints for surface roughness are not in millimetres, but in micrometres, which is one thousandth of a millimetre. The surface roughness values are often below micrometre (µm) and are in the sub-micron level (note, "micron" and "micrometre" are interchangeably used in this book, but both refer to the same 0.001 mm).

- Now switch over to inch. The numbers attached to the surface roughness are in millionths of an inch, as in 18 which is .000018 in or 18 microinches.

  One microinch (1 µin) = .000001 in
  One micrometre (1µm) = 0.001 mm

- The standard covering this area is ASME Y14.5M-1994. ASME stands for American Society of Mechanical Engineers. Suffix "M" on this standard indicates that the entire ASME standard is written in metric – a trend in recent years. More on this under "Engineering Drawings" (pages 40 and 41).

- In this short chapter, only the minimum amount of information is provided. Such standards such as print size, from Size A to F for inch users, and other related information are included in the ASME Y14, a family of 18 standards. The best source to find more about this standard would be www.asme.org.

Introduction to Metric Units

1 m
(Base SI Unit)

m

metre

- Always expressed in lower case "m" (as in "s" for second - the unit of time). "m" for metre is one of seven International System of Units (SI).
- Inch, on the other hand, was derived from and correlated with metre since 1959 when the directors of the National Metrology Institutes of the United States, Canada, England, Australia and South Africa agreed on 1 m = 39.37 in, and 1 in = 25.4 mm exact. (see page 90 for more information)

0.001 m
(1 mm)

mm

millimetre

- All metric blueprints are written in millimetres except for surface roughness values. For example, 4850 means "4850 mm", 0.3 means "0.3 mm", and zero after the decimal point is omitted in metric prints unless necessary. Zero must always be present in front of a decimal point when it is smaller than 1 mm (e.g. 0.7, 0.25).

0.001 mm
(1 µm)

µm

micrometre (official)
"micron" (common)

- Micrometre is often referred to as "micron". Micrometre (as in 3 micrometres) is a more official expression than "3 microns".
- Micrometre is one thousandth of a millimetre which, in turn, is one thousandth of a metre. Therefore, one micrometre is one millionth of a metre in the same manner one "microinch" is one millionth of an inch.
- In this Handbook, one micrometre (1µm) is often rounded to 40 millionths of an inch for simplicity whenever this rounding is appropriate. It should be .00003937 inch to be exact, but the rounded number .000040 will be adequate in this Handbook.
- It is in this unit, micrometres, that tolerances are often spoken. For example, 0.05 mm is expressed as 50 micrometres or "50 microns".

0.000 001 mm
(1 nm)

nm

nanometre

- Below micrometre is nanometre, which is one thousandth of a micrometre. Rarely in the machine shop practice will this unit be used. However nanometre is the critical unit in expressing the accuracy of gauge blocks. Typically, the highest grade gauge block is accurate within 25 or 50 nanometres. 25.4 nanometres equals 1 millionth of an inch (1 µin). Wavelength of the red He-Ne laser is 633 nm and gauge blocks are compared against this wavelength.

Introduction to Inch Units

.001

One thousandth (of an inch)

- On a noisy shop floor, one machinist may shout "one thou" (.001in) to another in place of "one thousandth". Shop-language is generally short; everyone understands what "one thou" is. On the blueprint one may find THRU, short for a "through hole".
- To measure thousandths of an inch, any caliper (dial, digital, or Vernier) should suffice when dimensions are not critical. Note, measured data obtained by hand-held calipers may contain personal bias (see Chapter 5 for more details).

.0001

One ten-thousandth (of an inch)

- Many machinists call this "one tenth" or "a tenth" for "one ten-thousandth", using the short form of shop language.
- The caliper is no longer acceptable at this level because it is inadequate to measure "tenths". A micrometer must be used instead to measure this dimension. "One tenth" in metric is 2.5 micrometres (2.5 µm) rounded. Its accuracy is ±2 µm for most of 0-25 mm micrometers, and ±.0001 in for 0-1 inch models.
- Up to this level of precision and when the size is limited to an inch or two, the issue of thermal expansion in metals may not be a big factor.

Measurements can be conducted at normal room temperature or on the shop floor up to this level, provided the workpieces are small.

Note that variation of temperature between the gauge and workpiece must be avoided.

↓

ARBITRARY LINE

.00001

Ten microinches (10 µin)
Ten millionths (of an inch)

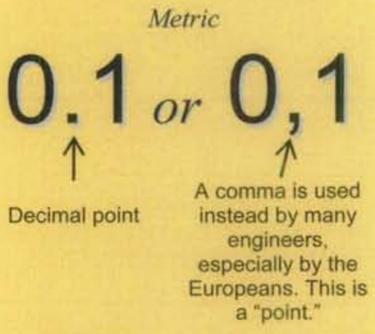
- A micrometer cannot measure ten millionths anymore. From hereafter one needs an electronic transducer called LVDT which is based on minute voltage variations caused by a probe movement. There are two major types of measurement: One is "Absolute" measurement (e.g. micrometers) and the other is "Comparison" measurement (e.g. dial indicators). Comparison measurement starts with gauge blocks and is superior.
- Temperature is definitely an issue at this level.

.000001

One microinch (1 µin)
One millionth (of an inch)

- The smallest dimension on blueprints, this is also the smallest resolution of measuring gauges. Smaller than one millionth of an inch does not exist in the metalworking trade. One microinch is 25 nanometres (25 nm) rounded. At this level, temperature and dimension appear to be united and hard to separate. Uncertainty value of the temperature gauge is a concern here.

Representation of Dimensions



- According to the ASME Y14.5M-1994 (American Society of Mechanical Engineers) standard, millimetre dimensioning must follow the following three rules:
  1. where the dimension is less than one millimetre, a zero precedes the decimal point,
  2. where the dimension is a whole number, neither the decimal point nor a zero is shown, and
  3. where the dimension exceeds a whole number by a fraction of one millimetre, the last digit to the right of the decimal point is not followed by a zero (e.g. 0.7 or 0.07, not 0.070)
- Decimal point is a point. European engineers tend to use a 'comma' where most others would put a point for a 'decimal point'. ISO standards also use a 'comma' where a 'point' is designated.

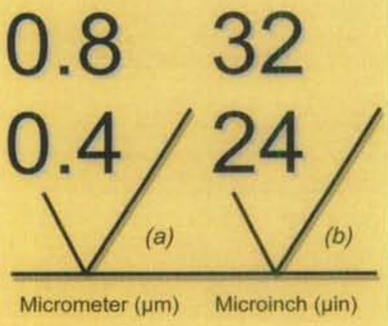
Which one is Metric?

(a) 0.25

or

(b) .250

- One of the two examples shown here is in metric. The answer is *(a)*. Where the dimension is less than one millimetre, a zero always precedes the decimal point. In contrast, here are the rules in inch dimensioning:
  1. a zero is not used before the decimal point for values less than one inch,
  2. a dimension is expressed to the same number of decimal places as its tolerance. Zeros are added to the right of the decimal point where necessary, as in .250.
- All engineers will be able to identify metric prints and separate them from inch counterparts intuitively without looking at the title block. The number 12 in a metric drawing should be 12 mm since all dimensions are in mm (except surface roughness values, see below).



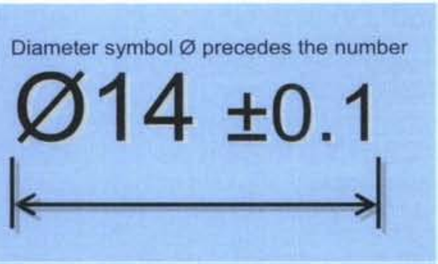
Surface Roughness Callout:

Units are in µm or µin

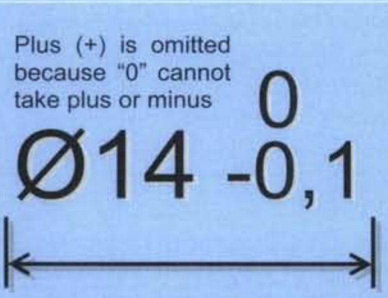
The value on top is the Upper Specification Limit or USL; the bottom, LSL.

- When surface roughness values are specified, the rule changes; the numbers are in micrometres. See example *(a)*: The upper spec limit for this surface is 0.8 µm, the lower limit 0.4 µm.
- Similarly for inch, the numbers are in microinches: example *(b)* indicates that the surface roughness must fall between 32 µin and 24 µin, presumably in Ra. (Ra is not a default but is often used)
- Single-digit surface roughness in inch system, for example 6 (.000006 in) or 4 (.000004 in) should be a highly polished mirror surface. Metric specifications in roughness often take numbers below 1 µm.

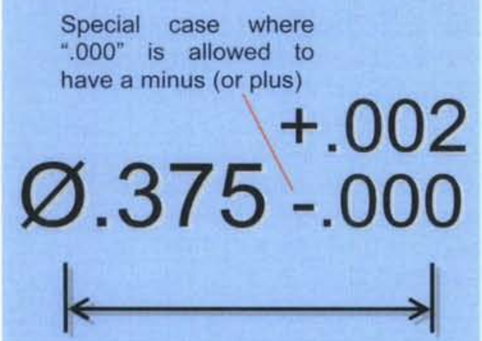
Dimensioning: Size Tolerances



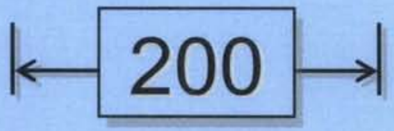
- Ø (Phi), a Greek letter, is the symbol for diameter that always precedes the number. In the old days the diameter was DIA, but has been replaced by the symbol Ø. SØ is assigned to indicate spherical diameters such as gauge balls.
- ±0.1 is known as "*Bilateral Tolerance*" as opposed to the "*Unilateral Tolerance*" described below.



- This is "*Unilateral Tolerance*" because the tolerance is given in one direction (-0,1). Bear in mind, a zero cannot take minus (-) or plus (+), so it is omitted, although it implies plus.
- This tolerance may be for a shaft (Outside Diameter, or OD), where the shaft may be fitted into a mating part in assembly. If the receiving bore is specified with Ø14+0,1, this condition will produce a "clearance fit" for this pair. Thus they are likely to fit with ease in assembly.



- Derived from 3/8, Ø.375 is a common inch specification. In the example at left, this diameter can be made larger than Ø.375 by 2 thousandths, but it cannot be made smaller than Ø.375. Such unilateral tolerance is commonly applied to inside diameters where a hole is expecting a shaft having Ø.375 to come through. Many choose a target size of Ø.376, the mid point.
- Using this example, a bore would have Ø.377 as the Least Material Condition (LMC), and a Most Material Condition (MMC) of Ø.375.
- Since a zero does not take plus or minus, to assign minus (-) zero is incorrect. It is allowed, however, in inch dimensioning to attach + or – to zero to the extent necessary: in this case -.000.



Basic Dimension (Theoretically Correct Size)

- 200 wrapped around in a box is known as a "basic dimension" which is defined as a theoretically correct size. It cannot therefore take tolerances.
- If this is the distance to a centre of a hole, a "true" position may be attached to the hole centre, because the basic dimension cannot take tolerance values.
- The number in a box may be used for angles as well: 45° for example.

International System of Units: SI
(Système International des Unités)

The International System of Units, abbreviated as "SI", officially is a system built upon a foundation of seven base units as outlined here. All other units are derived from these base units.

In the area of weight, particularly in hardness, this handbook uses Kg, which is one of the seven SI. 'N' for Newton is also widely used in describing the amount of force.

m *Metre (Length)*	► The metre is the length of the path travelled by light in vacuum during a time interval of one part 299 792 458 of a second. Metre is always expressed in lower case "m" as shown here. The SI unit of speed is the metre per second. Similarly, the SI unit of area is the square metre. Acceleration is defined by the metre per second per second.
s *Second (Time)*	► The second is the duration of 9 192 631 770 cycles of the radiation associated with a specific transition of the Cesium-133 atom. One of the functions of NIST is to keep track of seconds and broadcast it. They deliver digital timing signals by telephone and through the Internet.
K *Kelvin (Temperature)*	► The Kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The temperature 0K is commonly referred to as "absolute zero". On the more widely used Celsius temperature scale, water freezes at 0°C and boils at about 100°C.
Kg *Kilogram (Mass)*	► The international standard for the unit of mass, Kilogram is a cylinder of platinum-iridium alloy kept by the International Bureau of Weights and Measures (BIPM) near Paris. This is basically the same platinum-iridium alloy used to create the metre bar. This is the only base unit in SI still defined by an artefact.
A *Ampere (Current)*	► The ampere is the current which, if maintained in each of two infinitely long parallel wires separated by one metre in free space, would produce a force between the two wires (due to the magnetic field) of 2×10^{-7} Newtons for each metre of length.
cd *Candela (Luminous Intensity)*	► The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hertz (Hz) and that has a radiant intensity in that direction of 1/683 Watts per steradian.
mol *Mole (Amount of Substance)*	► The mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.0012 kilogram of Carbon-12.

Hierarchy of Precision

Standards

Both gauge blocks (No. 1) and ring gauges (No. 2) are the standards for gauges such as micrometers and calipers. Gauge blocks are for outside dimensions or OD, whereas ring gauges are for inside dimensions or ID. Although they are the top two in the list, that status does not preclude both to be used as Go/No-Go Gauges on the shop floor. (see Chapter 9 for more information on Go/No-Go Gauges)

Simplified and partial ranking

1 **Gauge Blocks**

2 **Ring Gauges**

3 **High-Accuracy Coordinate Measuring Machines**

4 **High-Accuracy Fixed Gauges**

5 **Micrometers**
Electronic Indicators
Electronic Height Gauges and more

6 **Calipers**
Dial Indicators
Mechanical Height Gauges and more

7 **Steel Rules**

No.1: Gauge blocks are the embodiment of precise length and are compared to the wavelength of a He-Ne laser.

No.2: Ring gauges are one layer below the gauge blocks, due to the fact that they are compared with the No.1 in the traceability hierarchy, i.e. gauge blocks. Both gauge blocks and ring gauges are available in a variety of accuracy grades.

Measuring Instruments

No.3: Considering its size, it is fair to place the CMM group above the micrometer. Some CMMs are extremely accurate while others are equal to or even below the level of micrometers, depending on the model. As a reference, the accuracy of a 0-25 mm (0-1 in) micrometer should be well within ±4 µm (ASME B89.1.13 standard).

No.4: A good example of fixed gauges are plug gauges. Their accuracy is generally 5 µm (.0002 in) above or below the nominal value which is engraved with a plus or minus symbol.

No.5: Most measuring gauges fall in either one of two groups in terms of resolution: 1 µm or 10 µm reading; in inch, 0001 or .001. Many common gauges such as mechanical indicators cover both high and low resolutions, as do many other conventional instruments. This and the next group are where the bulk of gauges belong.

No. 6: All calipers - digital, dial or Vernier-type - are below micrometers in the hierarchy of precision by roughly a factor of ten. The popular digital calipers generally offer ±20 µm (±.001 in) accuracy. The advantages of calipers over micrometers are numerous nevertheless. Calipers can measure inside, outside, steps, and they are usually 0-150 mm (0-6 in) in range. None of this can be done by a micrometer.

No. 7: Steel rules found in a tool box or in the pocket of machinists are still considered measuring gauges, but they belong to the bottom of this totem pole. They are affected by the parallax error of the human eye and as such the reading varies to a degree from one machinist to another. Moreover, 0.5 mm lines are the limit of engravings either by a chemical etching method commonly used or by laser (maximum 100 lines/inch for inch scales). This lack of finer discrimination puts steel rules at the bottom.

Summary

There are certain prerequisites in taking measurements. One is to understand the symbols on blueprints and the way tolerancing is expressed. Because of the limits of size, work geometry, surface roughness, and other specifications, several measuring instruments may be required to validate all features produced.

There is one school of thought on this. They say an acronym "**SWIPE**" is a good way to remember all essential elements in measurement. They are:

- **S** for Standard: It is always a good idea to review the pertinent standard. For example, ASME Y14.5M-1994 should be available whenever a workpiece is on the CMM and ready to go (see page 40).
- **W** for Workpiece: Quality of workpieces produced is the core issue in all manufacturing plants. It must meet the intent of the designer who produced the engineering drawing.
- **I** for Instrument: The old rule of thumb was to select a gauge that reads 10 times more than the total band of tolerance. In today's market, tolerances are so tight that a gauge to meet the 10 to 1 rule may be hard to find for extremely exact specifications.
- **P** for Person or Procedure: The person using a hand-held gauge himself would be a source of variance or bias. Calculating the variance between person A and B is briefly covered in this Handbook. (see page 56)
- **E** for Environment: This is a good reminder; all measurements ideally should be performed under 20°C (68°F) which is the standard (ISO1-1975).

The acronym **SWIPE** is mentioned here as a reminder. For more thorough discussion, obtain the '*MSA (Measurement Systems Analysis) Manual, Third Edition*' published by AIAG (Automotive Industry Action Group). Those who are in automotive fields may find other books AIAG books useful such as '*PPAP (Production Parts Approval Procedures)*'.

There are two major types of instruments: One is called "standard" and the other is called "gauge". A good example of a standard is a gauge block, by which traceability to NIST and to a physical constant is established. On the other hand, a micrometer is a "gauge" and is not a "standard". For this reason, to calibrate a micrometer several gauge blocks are required (See pages 142, 143).

PART II

Metrological Concepts

Part II:
Metrological Concepts

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- Before and After 1994
- Flatness and Parallelism
- Flatness Determined by CMM
- Third Angle Projection
- Straightness Variations Under MMC
- Measurement Strategies for Flatness and Parallelism

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- Roundness, Diameter and Cylindricity
- Cylindricity
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  [Source: ASME Y14.36M-1996]
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- Reading the Hard Copy (Aspect Ratio)
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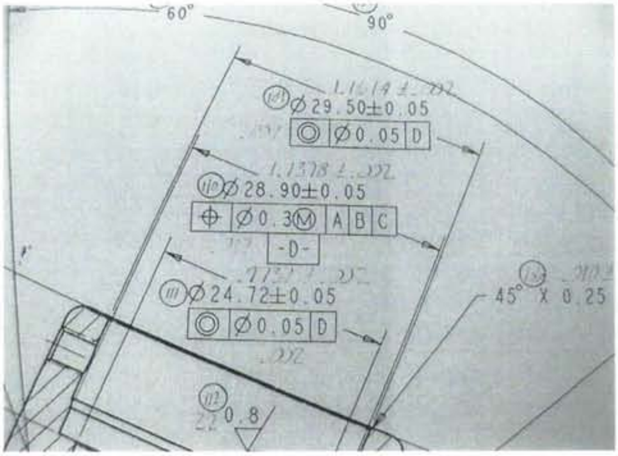
- Standard Reference Material (SRM) from NIST
- The Durometer

Chapter 3

Geometric Dimensioning and Tolerancing (GD&T)

"THE RULES ON ENGINEERING PRINTS"



To measure most precisely, one must recognise the criticality of dimensional tolerances assigned to a feature. Without knowing the rules on the engineering prints, the measurement cannot possibly start. One of the major reasons for the creation of measuring gauges was to validate dimensions and geometries specified on engineering drawings.

A broad selection of text books are available on Geometric Dimensioning and Tolerancing, or simply GD&T, including the current standard ASME Y14.5M-1994, which is a well composed standard with application examples. Among the books written on this subject, '*Geometrics III*' written by Lowell Foster outshines all others, though this is not for students without working knowledge of GD&T. The good news is that there are books of varying level on this subject, some with step-by-step approaches, while other textbooks may be more theoretical in nature. In this chapter, the reader will find the coverage of GD&T very brief and limited, for there are many other excellent books available written by qualified authors.

One subject Lowell Foster wasn't aware of during the 1960s when he and his followers were working on the concept of GD&T was the fact that the CMM, a major breakthrough in measuring equipment, was concurrently under development. Years later, GD&T and CMM became a pair inseparable; in need of one another. It should be understood that without CMM, the drawings written in GD&T would have taken a lot longer to verify at best. If the blueprint area is no longer blue, and they are in CAD, CMM will be the only answer.

The Universal Language for all Engineers

Originating in the U.S. in the 1960s and continuously updated up to this day, the GD&T is a global engineering language; used in design, production, and quality control; whenever geometry and feature of products must be specified. GD&T is an international standard of engineering drawings.

ASME (American Society of Mechanical Engineers) is the official technical body that represents the voice and opinion of the USA. ASME Y14.5M-1994 is the most widely used standard of the entire series shown above. In turn, it is validated by the distinguished mathematicians of the subcommittee Y14.5.1M. Its international counterpart is ISO 1101, which is a very concise standard of 20 plus pages.

In contrast, the ASME Y14.5M-1994 is more than 200 pages, and is filled with detailed application examples. The reader will be pleased with the extent and clarity of Y14.5M standard. All drawings and units are in metric: the "M" in Y14.5M signifies that.

For more information on this subject, read the definitive textbook by Lowell Foster, '*Geometrics III*' (Addison-Wesley ISBN 0-20-63342-6). If his book is too difficult to digest, there are instructional books on the market for entry-level engineers.

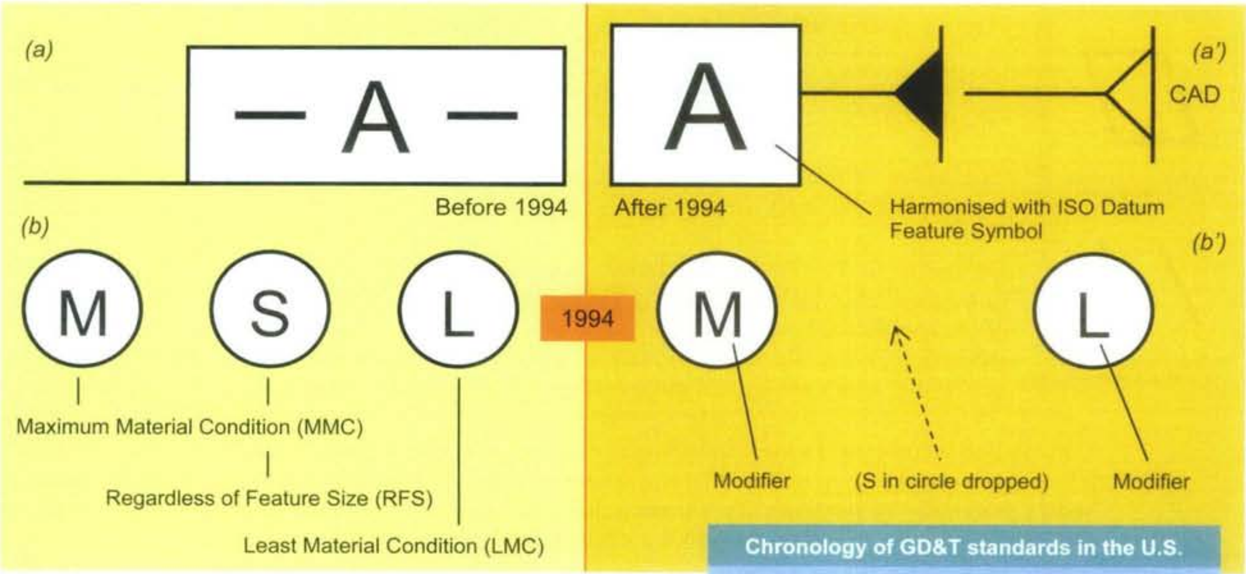
Y14.5.2 is a qualification program facilitated by ASME. Those who have acquired enough knowledge of GD&T may try either Technologist or Senior Level and receive a certificate. For more information, visit the ASME web site: www.asme.org

ASME Y14.1	Decimal Inch Drawing Sheet and Format	1995
Y14.1M	Metric Drawing Sheet and Format	1995
Y14.2M	Line Conversion and Lettering Format	(1992, Reaffirmed 1999)
Y14.3M	Multiview and Sectional View Drawing	(1994, Reaffirmed 1999)
Y14.4M	Pictorial Drawing	(1992, Reaffirmed 1999)
Y14.5M	Dimensioning and Tolerancing	(1994, Reaffirmed 1999)
Y14.5.1M	Mathematical Definition of GD&T	(1994, Reaffirmed 1999)
Y14.5.2	GD&T Professional Certification GDTP	(Qualification procedures)
Y14.6	Screw Thread Representation	(1978, Reaffirmed 1998)
Y14.7.1	Gear Drawing Standards — Part 1 Spur, Helical, Double Helical and Rack	(1971, Reaffirmed 1998)
Y14.7.2	Gear and Spline Standards — Part 2 Bevel and Hypoid Gears	(1978, Reaffirmed 1999)
Y14.8M	Casting and Forging	1996
Y14.13M	Mechanical Spring Representation	(1981, Reaffirmed 1998)
Y14.24	Types and Application of Engineering Drawings	1999
Y14.34M	Associated List	1997
Y14.35M	Revisions of Engineering Drawings	1997
Y14.36M	Surface texture Symbols	1996
Y14.38	Abbreviations and Acronyms	1999
Y14.100	Engineering Drawing Practices	2000
Y14.41	Digital Product Definition Data Practices (CAD)	2003

This is the Y14 standard most often quoted and taught.

The latest development to standardise CAD.

Before and After 1994



According to the official chronicles, the members of ASME Y14 GD&T standard committee met as many as twenty three times between 1982 and 1994 to finalise the 1994 standard. Among other updates brought into the latest version, the symbol change from *(a)* to *(a')* as outlined above represents a conscious effort on the part of ASME to embrace ISO-style Datum symbol expression.

Chronology of GD&T standards in the U.S.

2004	Next generation of Y14.5M
1994	ASME Y14.5M
1982	ANSI Y14.5M
1973	ANSI Y14.5
1966	USASI Y14.5
1963	MIL-STD-8C
1957	ASA Y14.5

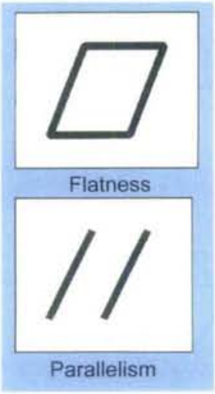
There are two types of blueprints in circulation in USA today: those prints written before 1994 (based on the 1982 standard and earlier), and those written after 1994. Luckily, identifying which one is which is simple: Compare *(a)* vs. *(a')* again. After 1994, the U.S. adapted ISO-specified blueprint expression under the banner of "harmonisation".

There are four GD&T symbols that are always applied on the basis of Regardless of Feature Size (RFS): (1) Circular Runout, (2) Total Runout, (3) Concentricity, and (4) Symmetry. RFS means "regardless of the size so long as it falls within upper/lower size limits". Circular Runout is based in terms of RFS, for example, and it cannot take MMC or LMC since it has nothing to do with diameter (a feature of size) but everything to do with the variation of Radii.

Any part within the upper and lower limits of size is a good part. Why does anyone need a modifier to indicate a normal condition? If RFS is the normal condition, why add a modifier S in circle? Therefore, the modifier was dropped after 1994, and everything is assumed as RFS unless a modifier (M in circle or S in circle) is attached. Again, RFS is implied unless "modifier" is entered into the feature control frame. Only when the modifier is added, then the standard rule (RFS) will be considered "modified".

Conversely, if modifier "M" or "L" in circle is not entered, it means RFS. This is known as the Material Condition Rule, or GD&T Rule No. 2. GD&T Rule No. 1, going backward, is also known as "Limits of Size Rule", or "Boundary of Perfect Form at MMC".

Flatness and Parallelism



Flatness: The condition of a surface having all elements in one plane.

Flatness Tolerance: A tolerance zone defined by two parallel planes within which the surface must lie.

Parallelism: The condition of a surface (or axis) which is equidistant at all points from a Datum plane (or axis).

Definition A: Parallelism Tolerance: A tolerance zone defined by two parallel planes (or lines) parallel to a Datum plane (or axis) within which the elements of the surface (or axis) of the considered feature must lie.
Definition B: Parallelism Tolerance: A cylindrical zone whose axis is parallel to a Datum axis within which the axis of the considered feature must lie.

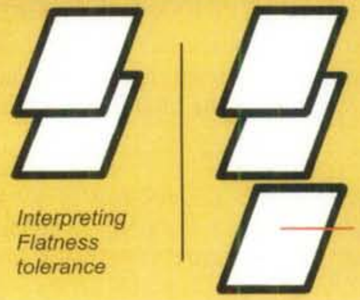
Flatness is a member of Form (Straightness, Flatness, Circularity, and Cylindricity), thus its definition is more geometric in nature. Flatness tolerance is a total zone as illustrated below, sandwiched by two theoretical ideal planes. To ascertain this zone, the minimum zone method is used in calculation. Unlike flatness, parallelism defines a relationship between the two members.

This zone must not exceed "Limits of size" (upper and lower size limits) and must be "perfect at MMC."

Flatness Tolerance as defined by ANSI Y14.5M is a minimum zone defined by two parallel planes.

The fundamental difference between the two, flatness and parallelism, is absence (Flatness) or presence (Parallelism) of a datum plane (or axis for shaft and bore).

Flatness does not consider a datum plane, whereas parallelism must have one. One needs to know parallel to which plane or axis, thus datum must be indicated.

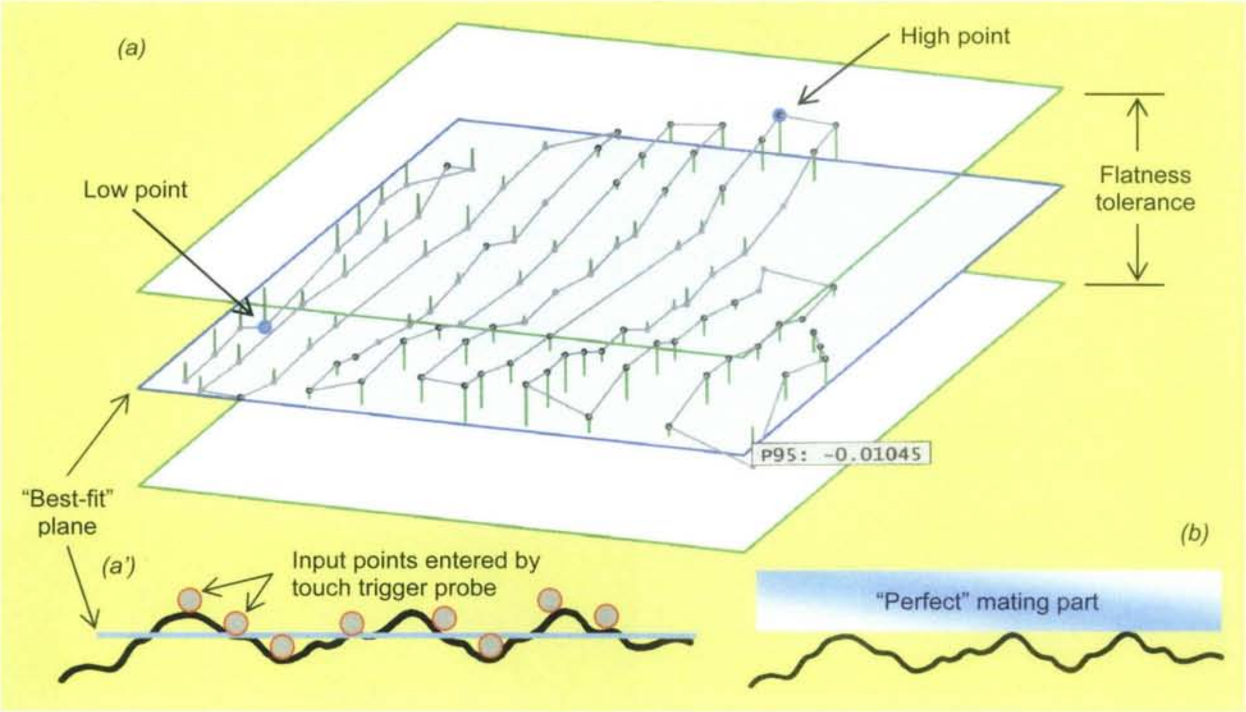


Interpreting Flatness tolerance

Interpreting Parallelism tolerance

Datum plane or axis required in parallelism.

Flatness Determined by CMM

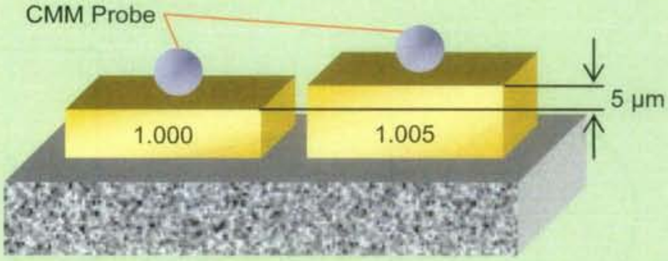


On a CMM, the "best-fit" plane as represented by the drawing *(a)* and *(a')* is determined by a number of discrete inputs entered into a calculation; the greater the number of inputs, the more trustworthy the data will be. The best fit plane is within the maximum minus minimum point region. Two parallel planes will make contact with the top and bottom points, while making sure the area sandwiched by them remains minimal.

From the drawing *(a')*, it should be clear that the plane established by CMM will be placed below the highest peak and above the lowest valley. As in most other cases, the "best-fit" plane is calculated by, among others, the minimum zone method.

If this method is objectionable, in view of the surface texture, the designer may specify a tangent plane for a plane. What if one surface is milled and its mating surface looks like a mirror as in the above example *(b)*? In theory, the highest three points will come into contact with such a fine milled plane. The question is how to locate those spots; an optical parallel or even a steel parallel may work: measure over it and subtract the thickness.

A flatness zone of 50 µm (.002 in) can be easily checked by all CMMs currently in use. Flatness of 5 µm (.0002 in), on the other hand, may or may not be that clear-cut. 5 µm may be the accuracy limit on some CMMs, while others are more accurate. One way to check if it is good enough for checking flatness is to test the CMM by using a pair of gauge blocks as outlined below:



Having two gauge blocks, in this example 1.000 and 1.005 mm, the top surface can be probed by touch probe repeatedly, 10 times on 1 mm block and 10 times on the other, for example. The Z-axis data should display a high degree of correlation. Try this with a pair of 1 mm and 1.001 mm block. It should still repeat well.

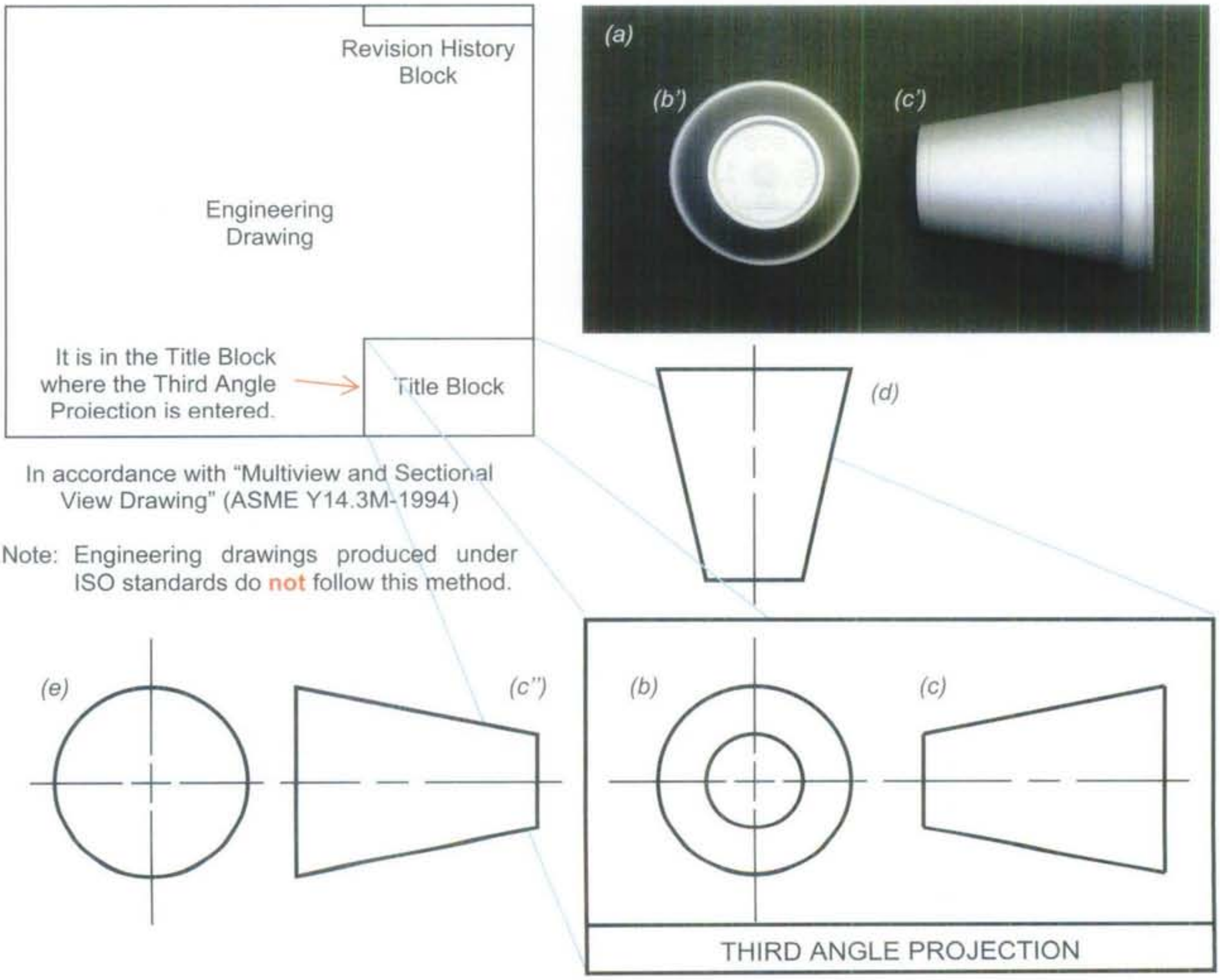
Third Angle Projection

From the paper cup shown below *(a)*, it should be clear as to which direction the product is turned to. The concentric circle shown in the box *(b)* corresponds to the bottom the cup *(b')*. Assume the bottom end is facing upwards when viewed directly overhead. The workpiece specified on the prints must be turned 90° into the direction indicated by *(c)* and *(c')*. And *(d)* is the direction into which a product is turned to show features.

Assuming that is that the cup is a solid piece, when turned one more time, it will reveal the flat bottom as indicated by *(e)*. Normally, the third angle projection is specified in the title block shown at the lower corner of the prints. When it is obvious, it can be omitted.

This explanation is based on ASME Y14.5M-1994, the current U.S. standard. Its counterpart in ISO flips it over the other way, and is called "First Angle Projection".

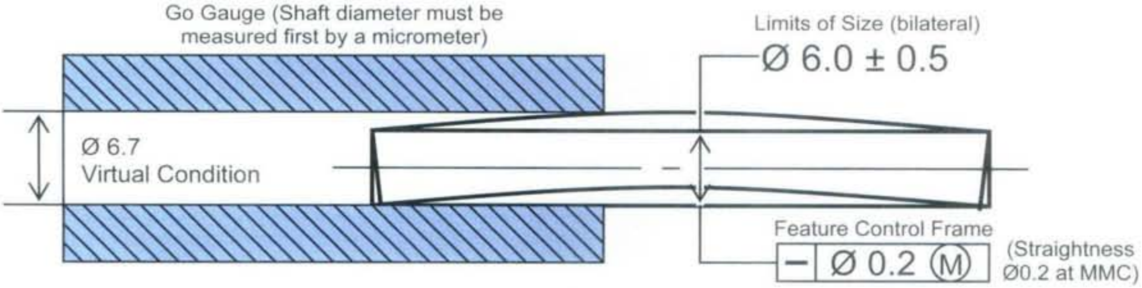
The Third Angle Projection is a standard under the ASME Y14.3M-1994 Multiview and Sectional View Drawings. In most instances, the third angle projection is obvious. However, if the workpiece is complicated, the third angle projection is likely to be added onto the drawing.



In accordance with "Multiview and Sectional View Drawing" (ASME Y14.3M-1994)

Note: Engineering drawings produced under ISO standards do **not** follow this method.

Straightness Variations Under MMC

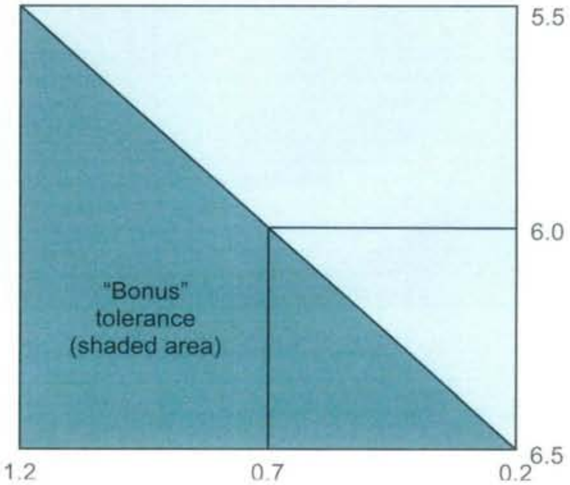


(a)

Unit: mm

	Size	Straightness	Virtual Condition
MMC ►	6.5	0.2	6.7 (Constant)
	6.4	0.3	
	6.3	0.4	
	6.2	0.5	
	6.1	0.6	
	6.0	0.7	
	5.9	0.8	
	5.8	0.9	
	5.7	1.0	
	5.6	1.1	
LMC►	5.5	1.2	

(b)



Maximum Material Condition (MMC) tends to give away "bonus" tolerance. Compare the above two charts *(a)* and *(b)*: They both refer to the same thing. The left chart *(a)* shows how straightness error is allowed under MMC, as the diameter of a shaft within the limits of size moves from MMC to LMC (i.e. from 6.5 to 5.5 mm). At its smallest shaft diameter 5.5 mm, the straightness (or out-of-straightness) can be as much as 1.2 mm.

All this "bonus" tolerance is possible only when MMC is specified in the feature control frame. For some shafts at the diameter to length ratio of 1 to 10 may flex, thus making a tighter straightness callout meaningless. What this specification tries to control is the axial straightness. In the case of a shaft or a bore, this is a common practice.

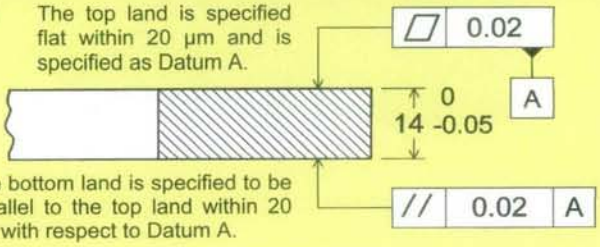
MMC was once loosely spoken in the shop as "the worst case". The straightness of 0.2 in diameter (this is specified on the axis) is the worse case that may be added onto the upper limits of size: 6.5. Together, the uppermost tolerance will be 6.7, which is known as "Virtual Condition", which remains constant as the chart *(a)* indicates.

Having understood that, one can produce a Go gauge representing a square slot of 6.7 mm wide. In it, rotate the workpiece and if it does not bind, the shaft is ready to go. Another Go gauge would be a ring gauge having 6.7 mm in diameter. However, it may not detect straightness error. In the end, the square slot may be the best answer. Yet another solution would be to place it on a granite surface plate and use a feeler gauge. See page 221 for one more solution using a cylindrical ruby probe.

Measurement Strategies for Flatness and Parallelism

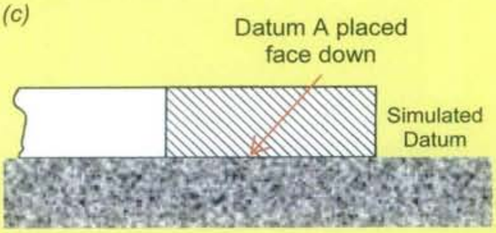
Datum A must face down as shown here to measure parallelism of the top surface relative to Datum A. Ideally, the stage must be large enough to hold the entire workpiece.

(b) The top land is specified flat within 20 μm and is specified as Datum A.



The bottom land is specified to be parallel to the top land within 20 μm with respect to Datum A.

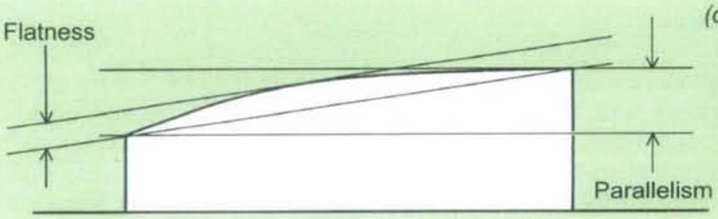
(c)



The definitions of flatness and parallelism are shown on the preceding pages. Let's see how they can be checked. There are three potential methods as listed above. The drawing *(b)* on this page is a hypothetical example where flatness and parallelism specifications happen to be the same.

The method *(c)* shown here is the easiest. Datum A must face down to check parallelism, because parallelism implies the relationship between two geometric elements, in this case two flat faces.

In contrast, flatness cannot take Datum. It is only compared against its own ideal and mathematical flat surface. In drawing *(d)* below, it is tilted to indicate the difference between the two.



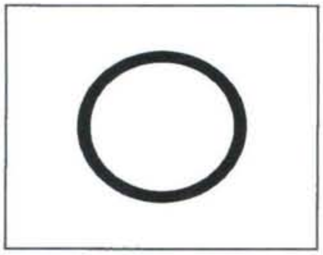
(d)

Flatness must remain within the Parallelism zone. Flatness specification can be equal or less than the value of Parallelism.

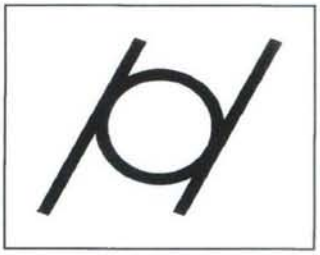
Chapter 4

Roundness and Cylindricity

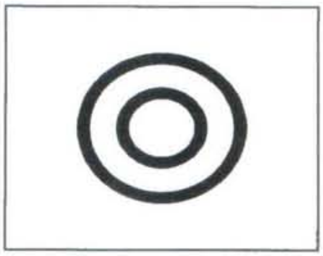
According to a number of experts in the field, there are more round parts than flat ones in the manufacturing industry. Imagine a bolt circle with six through holes: all of them, including the bolt circle itself, must be round. If the workpiece resembles a doughnut, then concentricity may also be specified on top of the circularity. There is also the issue of the "true position" (now called "position") controlling the hole centres.



Circularity



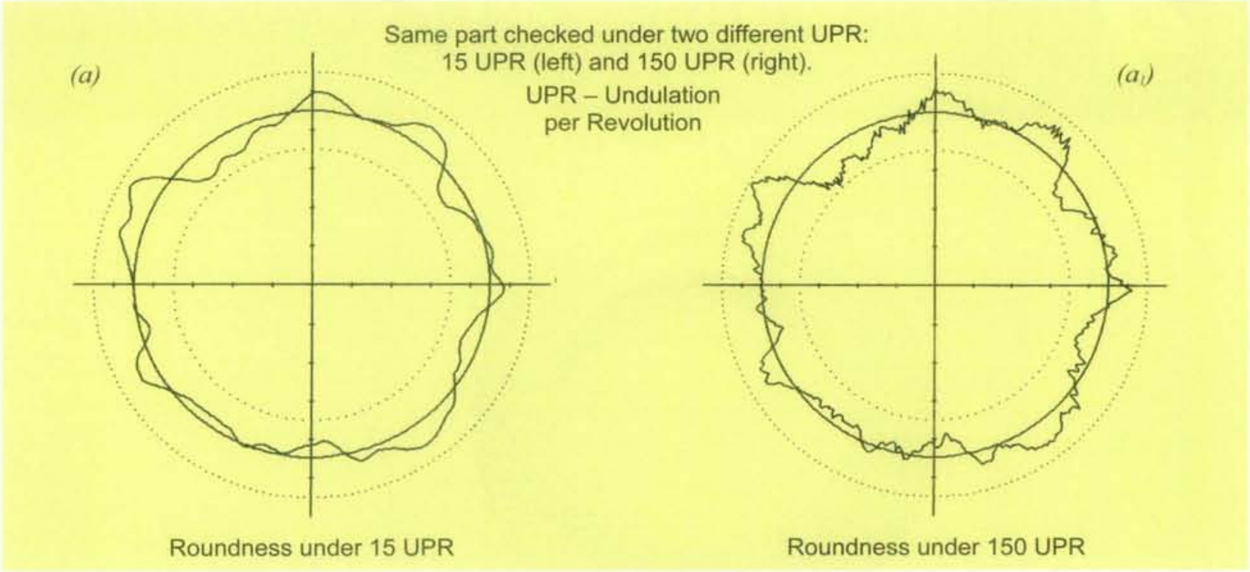
Cylindricity

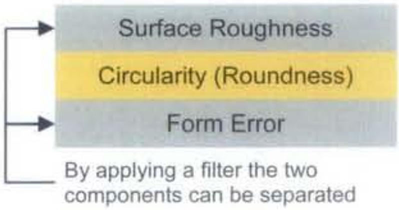


Concentricity

Roundness is measured from a slice, cut perpendicular to the axis of a cylinder. Lack of roundness is problematic for parts that rotate: It will cause vibration or heat if they are not round enough. This chapter uses the following three terminologies interchangeably to describe it: roundness, out-of-roundness, and circularity. Cylinders will also be looked at, because without it there will be none of the three symbols shown above. Surprisingly, they have nothing to do with diameter, since size is not an issue. The real issue here is the "feature of revolution", as described by the problems of lack of roundness above. The upper and lower tolerance limits are expressed in terms of "total zone", with no plus or minus, since only the limits of size can be specified with plus/minus.

Circularity (Roundness)





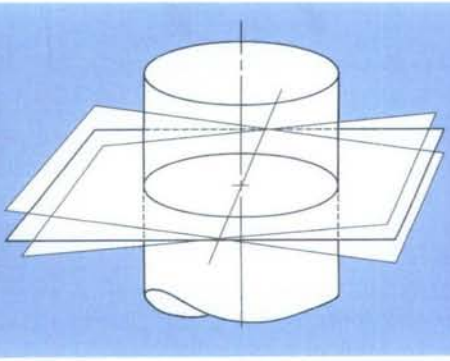
If the surface roughness component occupying the top surface can be removed by filters, the feature of circularity will emerge from beneath the surface. Three layers are shown at left: surface roughness, circularity, and form. These 3 properties are integrated and intertwined elements of a single part. They must be separated to look at the next level — circularity — which is among the most basic of all geometric elements.

Assume there was a chattering motion on the part of the turning machine as it removed the stock. Such motion would be imprinted on the work surface, effectively leaving a DNA signature on the part. For quality engineers, excessive circularity error would mean vibration, heating, and eventual failure, if this is a shaft designed to rotate at high speed.

By changing undulations from 15 *(a)* to 150 (a_1), engineers can learn the consequences of this shaft running at high speed. Though in GD&T, dynamics of revolution, for example at 7000 rpm, is not fully addressed because they are primarily concerned with form rather than function.

Circularity is a condition of a surface of revolution in which all points of the surface are equidistant from a common axis [ASME Y-14.5M -1994]

Circularity Tolerance: A circularity tolerance specifies a tolerance zone bounded by two concentric circles with-in which each circular element of the surface must lie [ASME Y-14.5M -1994].

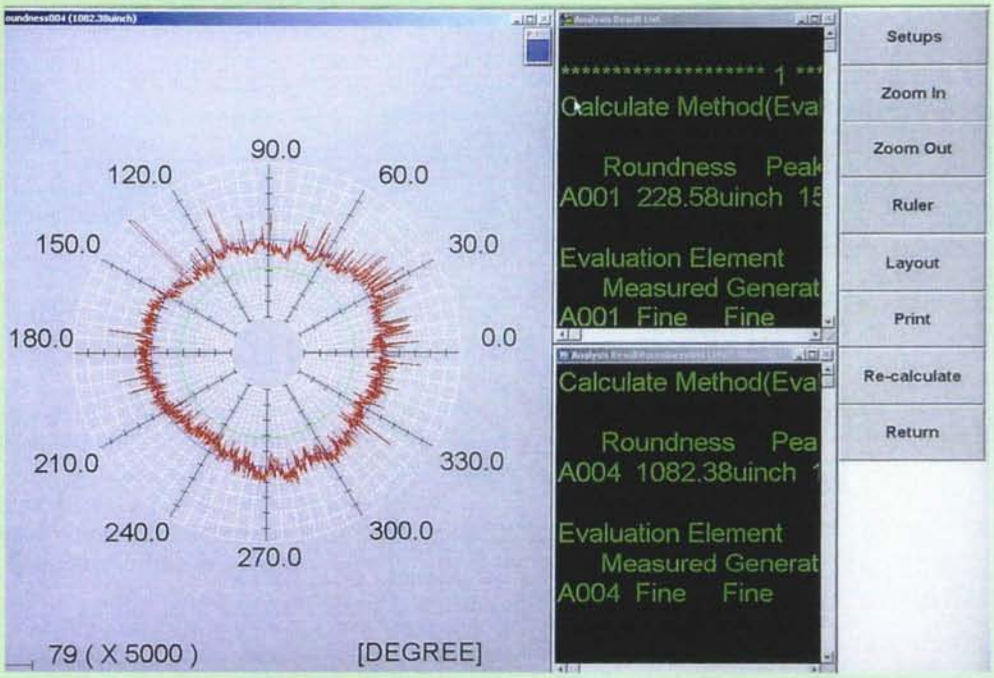


Circularity can also be understood as the product of two basic geometric elements: cylinder and plane. The condition states that they must meet normal (90°) to each other. The top surface of this cylinder may provide such a land if its cross-section is cut perpendicular to the axis.

Roundness, Diameter and Cylindricity

Roundness is very different from diameter. In fact roundness is not a feature of size such as diameter, but instead refers to the variation within an infinite number of radii. If all radii are equidistant from a single shared centre, such object will be perfectly round. However, as shown on this page, a perfectly round workpiece may not exist. The best artefact, the Roundness Standard shown on page 52, is not exactly round if data is assumed to be correct.

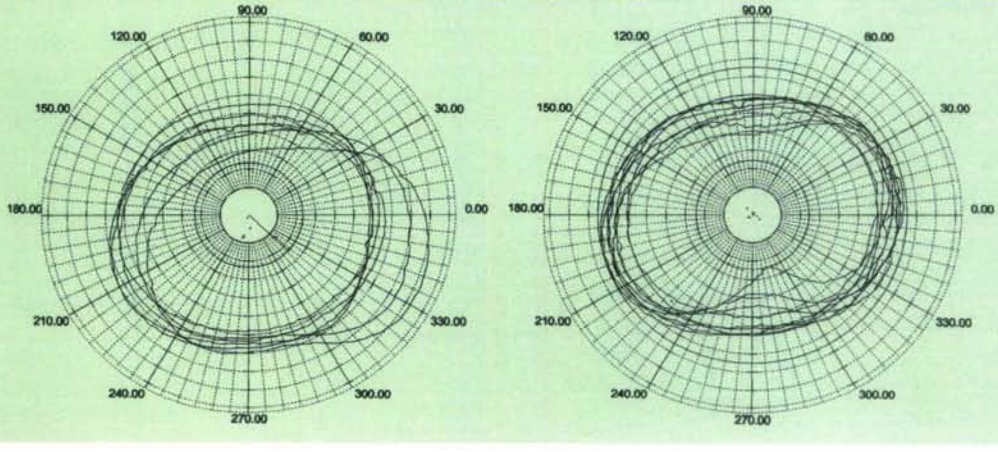
It is also important to recognize the difference between the roundness and cylindricity — a 2D and 3D concept respectively. Roundness is an independent single slice produced perpendicular (normal) to the axis, magnified to show out-of-roundness condition, whereas cylindricity is a 3 Dimensional concept. Both belong to the GD&T category called Form (explained later in this chapter). Both have nothing do with the diameter, but everything to do with the "surface of revolution".



```
******************** 1 ***
Calculate Method(Eva

   Roundness   Peak
A001  228.58uinch  15

Evaluation Element
   Measured Generat
A001  Fine    Fine
```

```
Calculate Method(Eva

   Roundness   Pea
A004  1082.38uinch  1

Evaluation Element
   Measured Generat
A004  Fine    Fine
```

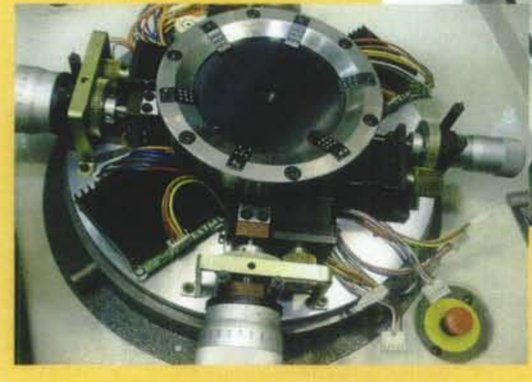
Roundness being tested in a roundness machine. The ability to zoom in and out is a useful feature to review details on the monitor.



Multiple traces of Roundness reveal the Cylindricity of the workpiece.

Cylindricity

The turntable and probe from which roundness is checked. Micrometer heads at the 4 corners adjust the levelling and centring of the workpiece.



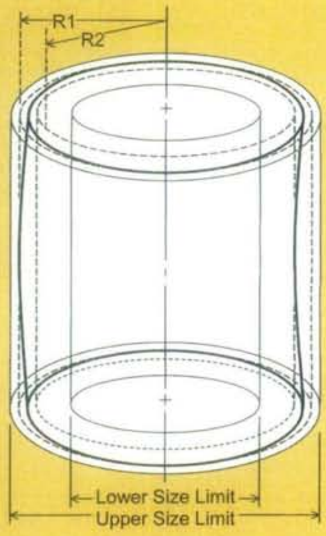
The turntable disassembled. This dish turns "true" within 25 nm (.000001 in) typically.

Cylindricity is a concept based on "surface of revolution", which must lie within the zone specified by its tolerance.

Cylindricity is not related to the diameter.

The diameter is a "feature of size" and as such it must have upper and lower size limits.

Cylindricity, which takes a "form tolerance" based on the total zone cannot exceed size limits. In the GD&T this is known as "Limits of Size Rule" or Rule No.1. Moreover, cylindricity spec is always smaller than the diameter spec by at least a factor of 2 to 1.



⌭

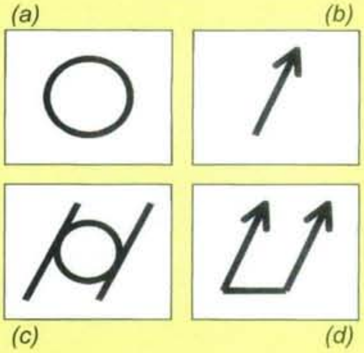
Cylindrical parts produced by turning and other machines can be checked by a roundness machine with a solid, square upright column that controls the vertical movements of the probe. The round upright column tends to measure roundness only, whereas the square one can detect cylindricity. The GD&T symbol for cylindricity is a composite of two requirements: (1) the surface of revolution must be round, (2) the surfaces must stay parallel to each other (within the total zone specified).

Journal bearings for crankshafts and camshafts must stay cylindrical: to be round may not be good enough for certain products that rotate at high speed, as are many other moving parts. Cylindricity is, however, a static concept. In the end, the workpiece must still be tested by rotating it at various speeds to see if it generates vibration. A balancing machine is employed for this reason.

Cylindricity is a condition of a surface of revolution in which all points of the surface are equidistant from a common axis. Cylindricity tolerance specifies a tolerance zone bounded by two concentric cylinders within which the surface must lie.

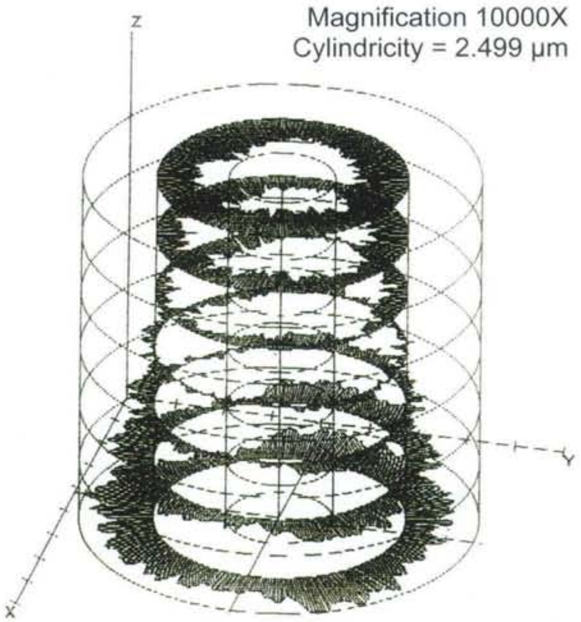
This is one shortcoming in the CMM. That is, to measure any one of four symbols at right, the CMM cannot magnify the traced data as effectively as the machine shown on the facing page. With the CMM, the smallest resolution on the display is how far one can read.

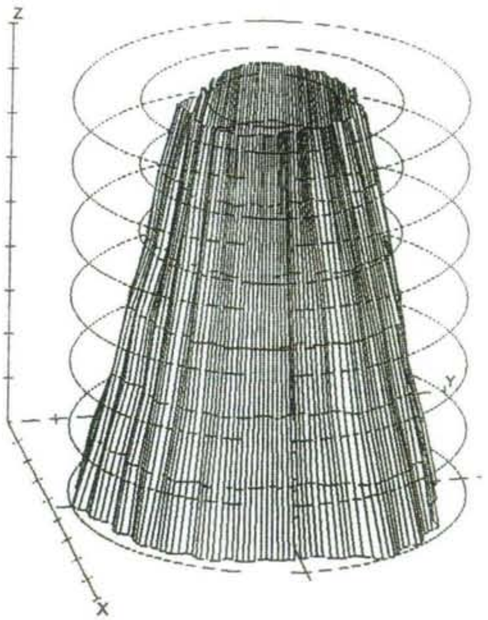
A dedicated machine such as the Roundness Tester is far superior to do the task assigned than a general-purpose machine like the CMM. The data density is much higher because the probe stays in contact with the work surface. In fact, the data density appears to be unlimited due to the bottomless memory. The 3-D plot below is generated by testing a plug gauge.



There is a difference between the symbols on the left *(a) (b)*, and on the right *(c) (d)*. All four start with a common axis. Circularity *(a)* looks into the radial variation, as does cylindricity *(b)*. Both are known as Form. Runout *(c)* and *(d)* specify how to measure.

Cylindricity tolerance is a composite control of form which includes circularity, straightness and parallelism of opposed elements. From the design engineer's point of view, cylindricity tolerance is an effective way to prevent cone.





Same cylinder under a different mode

Roundness Standard

The roundest of all round artefacts. This standard is within 10 nm in roundness (also known as circularity in GD&T). Graduations on this chart are 1 microinch (.000001 in) or 25.4 nm. This hemisphere was tested at NIST

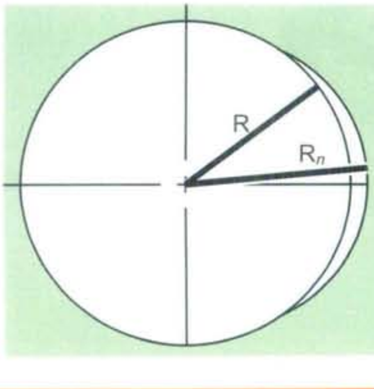
Unit: nanometer (nm)

NIST Test No. 821/265364-01 Serial No. 6664 (MM041)	
Position (Deg)	Deviation (R)
0	-7 nm
30	-7 nm
60	-2 nm
90	+5 nm
120	+8 nm
150	+5 nm
180	-7 nm
210	-10 nm
240	-2 nm
270	+8 nm
300	+5 nm
330	+4 nm

NIST Report of Calibration
Uncertainty: ±16 nanometers in K=2.

This hemisphere roundness standard was calibrated at NIST and its roundness is within a single-digit nanometre range as shown on the table at left. Loosely speaking, this standard is extremely round and near perfect. Circularity (also known as Roundness) of this object is compared against its theoretically perfect counterpart. Note, circularity (roundness) is nothing to do with the diameter and everything to do with the radial variations as in R and R_n as illustrated below and left. If this is a "perfect" circle, there will be no deviations among all radii calibrated. In real life, however, all round parts are more or less out-of-round in the magnitude of microns or sub-microns. The above hemisphere is the closest physical representation of roundness.

The hemisphere standard shown here is employed or to check rotational accuracy or runout of the turntables on page 50.

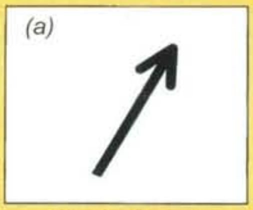


Radial variation (the difference between R and R_n) is certified in the NIST report of calibration at left. The expanded uncertainty in K=2 at NIST is ±16 nm which is far greater than the radial deviations reported.

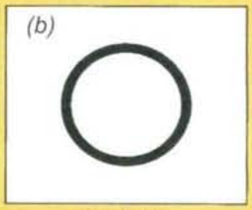
Circular and Total Runout

The symbols *(a)* and *(a')* are easy to guess: Runout. The difference between the two is clear. Top: Circular Runout *(a)*. This may be considered as a spot check, Bottom: Total Runout where the entire surface specified must be checked. Each Datum must be included in the feature control frame.

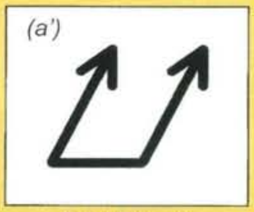
When either one of two Runout is specified *(a)* or *(a')*, the workpiece must be rotated 360° about a datum indicated on the blueprint.



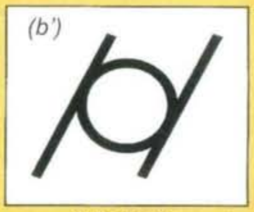
Circular Runout



Circularity



Total Runout



Cylindricity

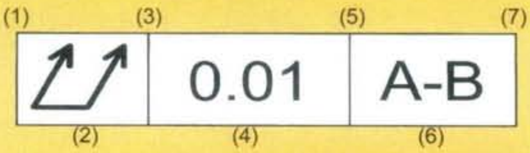
Circularity (also known as roundness or out-of-roundness) and Cylindricity on this column belong to a larger category called Form.

Both are expressed in terms of theoretical and ideal form. A round part is compared against its perfect counterpart. Hence, "out-of-roundness" is used in place of "circularity".

Both Circularity and Cylindricity are specified on prints independent of Datum. They are not bound by or implied to any Datum.

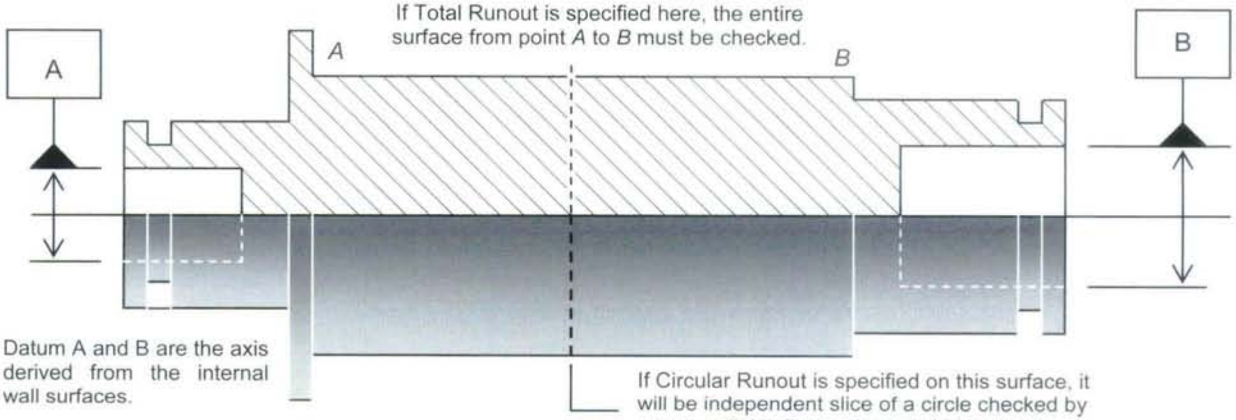
As its symbol suggests, Circular Runout (one arrow only) is a less stringent requirement than Total Runout. The Circular Runout controls only the circular element of a surface cut perpendicularly to the axis. Each Circular Runout is independent, because it does not have a connecting bar as in Total Runout. It is applied independently at any surface of revolution as the part is rotated 360° about the datum axis. Each circular element must be "within" the full indicator movement (FIM).

The measuring gauges most often used to check this are either test or dial indicators. The gauge must be placed normal (90°) to the surface so as to avoid cosine error. Runout of cone can be checked by any indicator placed normal to the surface of cone.



Unorthodox and not normally taught in official GD&T textbooks is a reading method as follows: (1) "This feature shall have" (2) Total Runout (3) "within" (4) 0.01 mm (5) "with respect to" (6) a compound datum A-B (7) "total wide."

By stating "within" and concluding the sentence with "total wide," this method enforces the concept of tolerance zone on which all 14 GD&T symbols are based. In other words, there is no minus value in the concept of GD&T.

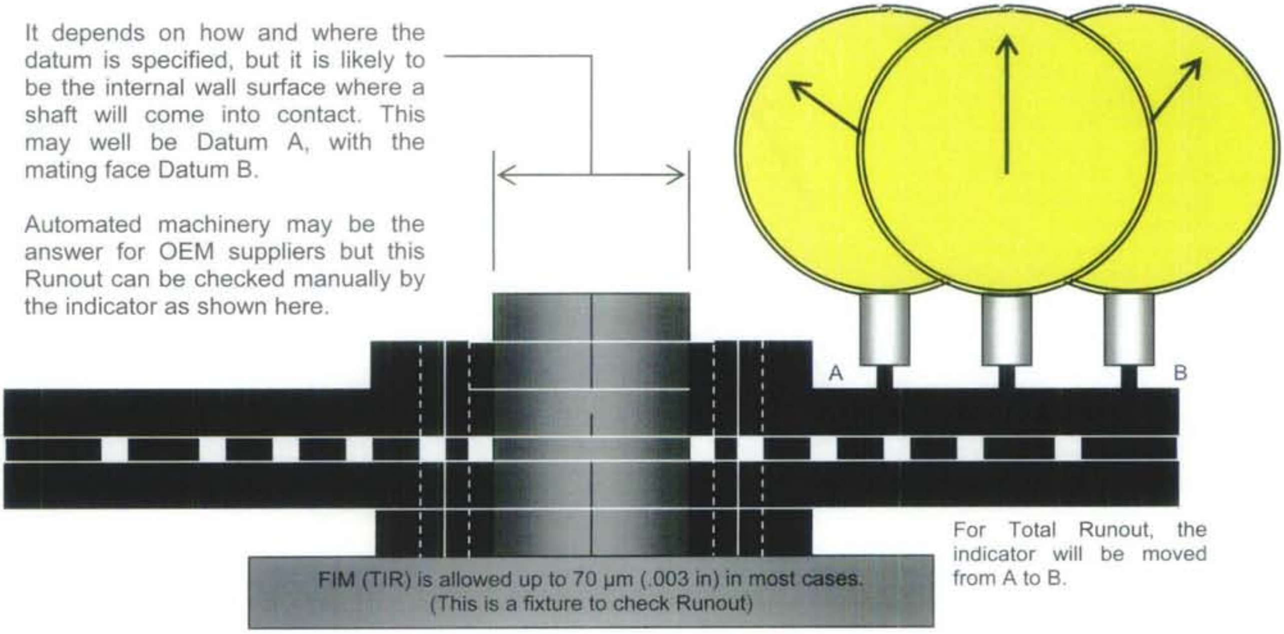


If Total Runout is specified here, the entire surface from point *A* to *B* must be checked.

Datum A and B are the axis derived from the internal wall surfaces.

If Circular Runout is specified on this surface, it will be independent slice of a circle checked by a test or dial indicator through 360°.

How to Check Runout



It depends on how and where the datum is specified, but it is likely to be the internal wall surface where a shaft will come into contact. This may well be Datum A, with the mating face Datum B.

Automated machinery may be the answer for OEM suppliers but this Runout can be checked manually by the indicator as shown here.

FIM (TIR) is allowed up to 70 µm (.003 in) in most cases.
(This is a fixture to check Runout)

For Total Runout, the indicator will be moved from A to B.

Normally, Circular or Total Runout is specified on a shaft or tube that rotates. The definition of Runout is documented in the Geometric Dimensioning and Tolerancing (GD&T) standard, ASME Y14.5M-1994, in which Runout is specified on a "surface of revolution". Such cylindrical parts may include flanges or routers, of which the disc brake depicted above is an excellent example. The horizontally extended router from the rotating shaft could be specified with either Circular or Total Runout. Both can be specified on a cone regardless of its angle. In the case of the above ventilated disc brake router, the angle happens to be 90 degrees to the axis. Runout callouts are often found on the automotive parts that rotate.

The features specified by Runout callout are always rotated; therefore the datum axis must be present and indicated in the feature control frame. It does not specify speed of rotation; for that the parts must be balanced by a balancing machine.

TIR, FIM and Runout

Full Indicator Movement, or simply FIM (current terminology), is a word more or less interchangeable with Runout. It is often used in automotive components because many of their parts rotate, and excessive Runout leads to noise and vibration.

The old terminology, Total Indicator Reading (TIR), was spoken by many machinists for at least several decades. If the indicator goes to the left-hand side of the dial and reads minus 2, and then goes to the right-hand side and reads 3. The TIR would then be 5. What is specified by TIR is no plus or minus, but a zone, based on the concept of total zone. Plus/minus is used only for the features of size (e.g. diameter, width, etc).

FIM confirms and enforces this basic concept. It is a concept based on a total zone, on which all GD&T tolerances are constructed; (True) Position is a good example.

Chapter 5

Measurement Basics

"TO GET THE MOST ACCURATE MEASUREMENT"

With all practical applications of measurement, there will always be some level of uncertainty: when a workpiece is measured, you will expect it to always be the same, but this is not always true; it may be a little more, or a little less, even when the same operator performed the measurement with the same measurement tool. The aim of this chapter is for operators to recognise how much of this is due to human error or equipment error, and how to effectively minimise it.

By introducing the two theoretical concepts of Gauge Repeatability and Reproducibility, and Abbe's Law/Principle for micrometers and calipers, operators can easily identify causes of variations in measurement using hand tools, and take measures to correct them. For example by considering the impact of Abbe's Principle, operators can choose the optimal tool to measure a workpiece with, considering their tolerance limits. With this knowledge, operators can be more confident that the measurements produced by their hand are the most accurate ones possible.

Gauge Repeatability & Reproducibility (GRR)

$$\text{GRR} = \sqrt{(\text{EV})^2 + (\text{AV})^2}$$

Gauge R&R

Equipment Variance (Repeatability)

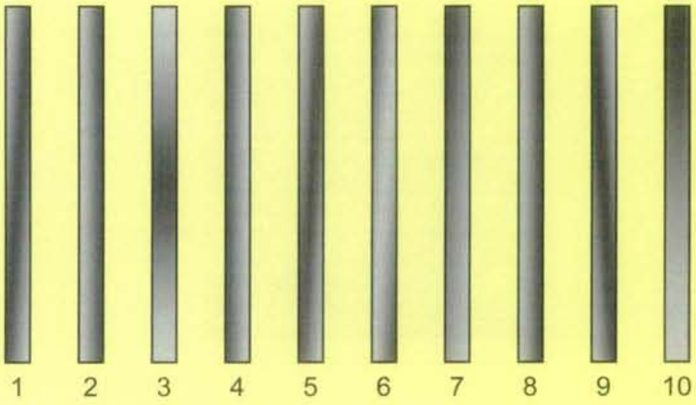
Appraiser Variance (Reproducibility)

As this simple equation shown at left suggests, the Gauge R&R is composed of two major factors: Repeatability (the first R of Gauge R&R) and Reproducibility (the second R). Repeatability is abbreviated as EV, for Equipment Variance, and similarly Reproducibility abbreviated as AV, for Appraiser Variance.

The amount of repeatability, or the variations in repeated measurements, is categorised as EV in the '*Measurement Systems Analysis (MSA) Manual*', and the variations among appraisers who share the same micrometer and measure the same parts are known as AV.

How to calculate EV and AV is explained in the MSA Manual in detail, available from the Automotive Industry Action Group (AIAG) in Southfield, MI. A typical hand-held gauge, such as a micrometer, exhibits a small bias depending on who is using it. Such amount is quantified and analysed in the MSA.

The Average Method to Find GRR

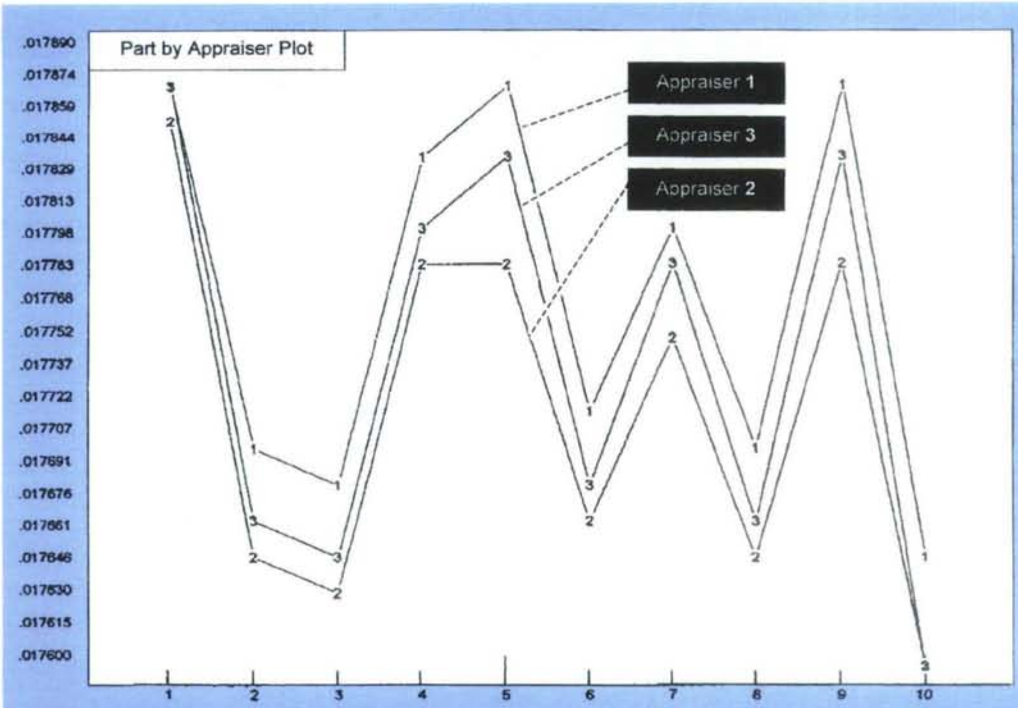


These 10 randomly selected production parts are thin strips of metal machined to a thickness tolerance, and ready for the next process.

Although numbered here, the appraisers have no idea as to which part is presented for them to measure. The facilitator who knows which on is which must mask the parts' identity.

An experiment was conducted. First, 10 actual parts were selected from the production floor, as shown above. Second, pick three operators (appraisers) on the floor who measure those parts on a day to day basis. Third, have Appraiser 1 measure all of them in a random order with a specific micrometer. Ask him or her to measure the same 10 parts randomly a second time. Optionally, try once again a third time. Ask Appraiser 2 and 3 to do the same with the same micrometer that Appraiser 1 used, and gather the data from all three of them.

In this case, there will be a total of 90 raw data. Since the same gauge was shared by all, and the same 10 parts are measured by three Appraisers in a random order three times; if a variance is found in the data, it reflects personal bias in using the micrometer. For simplicity, only results for part No. 5 are shown on the facing page. Each appraiser measured it three times randomly, so only nine raw data are shown.



Courtesy:
Gordon Skattum

This chart, Part by Appraiser, is sensitive to small variations in the data set.

A graphical presentation is a powerful tool in detecting and quantifying what is known as between-appraiser variations (AV).

The compactness of the data must be taken into account since the graph magnifies small variations.

Horizontal axis on this chart numbered 1 to 10 represents the 10 parts. Each one of three appraisers, Appraiser 1 through Appraiser 3, measured all 10 parts three times randomly with the same micrometer and the average value of each was plot. From this chart, it is clear that each appraiser holds micrometer and measures parts differently. Each Appraiser is consistent: no line in this chart crosses another, and all three measure large parts large and small parts small with excellent repeatability (see highlighted numbers in the table).

It is clear from this Gauge R&R study known as "Part by Appraiser Plot", that Appraiser 2 always and consistently measures the same part smaller than other Appraisers. On the other hand, Appraiser 1 measures consistently with a lighter touch. Between the two is Appraiser 3 whose line in the graph never touches the others. While all of them are separated in the graph, that distance between them is extremely small.

Two conclusions can be drawn from this study: (1) presence of personal bias (AV) certainly exists, as the above chart clearly suggests, (2) compactness of the variance among three Appraisers, and among nine measured data (left) remains tight.

All three Appraisers are probably seasoned veteran machinists. This data strongly suggests that each one knows exactly how to measure thin parts with a micrometer. In fact, the numbers are so closely correlated that another study like this may be hard to find. It also shows how well the micrometer performed in this Gauge R&R study.

Unit: inch

Appsr.	Trial	Part #5	Part #5 Ave
1	1	.0182 in	.018133 in
	2	.0181 in	
	3	.0181 in	
2	1	.0180 in	.017966 in
	2	.0180 in	
	3	.0179 in	
3	1	.0181 in	.018066 in
	2	.0180 in	
	3	.0181 in	

This is the raw data for part #5 collected randomly from the three appraisers: 1, 2, and 3. What is remarkable is the tightness of within-appraiser-variations as well as between-appraiser-variations. The range (Max-Min) of nine data is only .0003 in (7 μm) and .000167 in (4 μm) in averaged data.

The Range Method to Find GRR

Part No.	Appraiser A	Appraiser B	Range [A-B]
1	51.26	51.27	.01
2	51.27	51.25	.02
3	51.26	51.26	.00
4	51.26	51.24	.02
5	51.26	51.25	.01
		R-Bar	.06
		Average Range	.012
		Gauge R&R ŝ	.0101

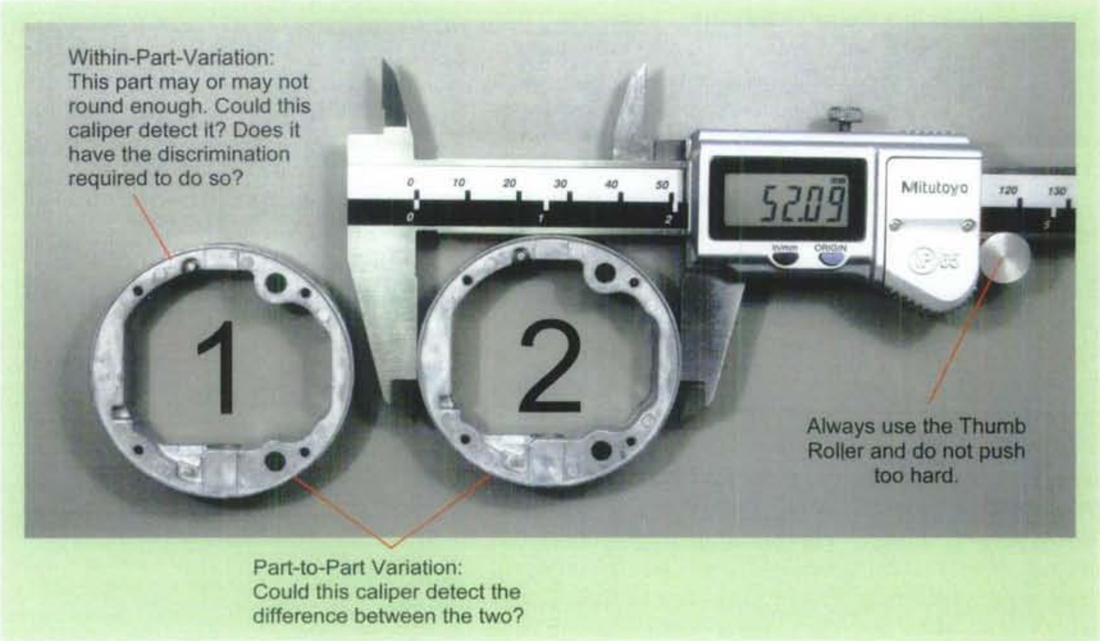
Divide the Average Range by the constant 1.19 to determine the GRR standard deviation.

Data gathered through measuring instruments is often trusted to be "correct", but measurements cannot be perfect. The reliability of any hand-held gauge is determined by the skill of the operators. The Gauge R&R Range method presented here may shed light as to the variation between the two operators using the same measuring gauge. For more complete information, see the '*Measurement Systems Analysis Reference Manual, 3rd Edition*', published by the Automotive Industry Action Group (AIAG) in Southfield, Michigan. Simply stated, the aim of having a measuring gauge is to find "within-part" and "Part-to-Part" variations.

The average range is divided by the constant 1.19 from Duncan's d*2 Table to estimate the GRR standard deviation (combined gauge error) for any study design of 5 parts, two appraisers and one trial. The ratio of GRR error to the limits of size (± 0.1 mm) can also be assessed.

$$\% \text{ GRR} = \text{GRR } \hat{s} \,/\, (\text{Tolerance} \,/\, 6) = 30\%$$
$$\% \text{ GRR} = 0.0101 \,/\, 0.03333 \times 100 = 30\%$$

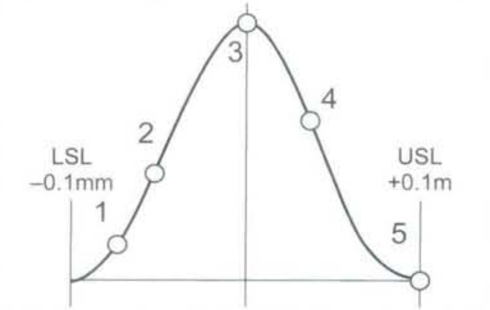
The Range Method provides only a quick and limited assessment of combined Gauge R&R error. To determine the larger contributor, AV or EV, a more complete GRR study (Average and Range method) is required based on multiple trials (two trial measurements for each of three appraisers for a total of 60 data).



Choosing the Correct Tool

Is a caliper acceptable for an application? The answer may lie in the Gauge R&R study. According to the data produced on the facing page, where 2 appraisers A and B measured 5 parts once with a shared digital caliper. Based on this small sample (only 5) the Gauge R&R is 30% of the size tolerance. In an incoming inspection based on the blueprint tolerance, this system should be sufficient, but there is a slight possibility to reject a "good" part (in tolerance) and accept a "bad" one. Although the raw data values on the facing page are good enough for a digital caliper reading to 0.01 mm, the %GRR to tolerance is at the borderline. Although skilled machinists can measure such a diameter repeatedly within ±0.02 mm with a digital caliper, novice operators must be shown how to measure parts with a caliper correctly.

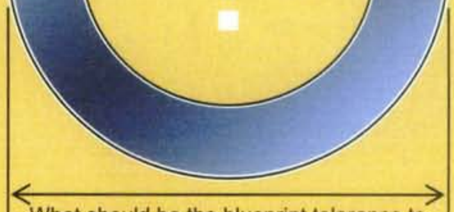
The 5 parts can be selected in this fashion. (But for Range Method this is not essential)



LSL=Lower Spec Limit / USL=Upper Spec limit

In this example, a tolerance of ±0.1 mm is measured with a digital caliper. The accuracy of the caliper is expected to be within ±0.02 mm. The gauge discrimination is 0.01 mm or 10 µm.

Therefore, the gauge on the facing page is reading 20 times better than the tolerance band (±0.1 mm = 0.2 mm in zone). The selection appears to be correct. Or is it? Gauge R&R (MSA) short study or range method answers this question.



What should be the blueprint tolerance to gauge resolution ratio? 10 to 1?

Marking the part to identify the point to measure is a method to prevent form error, known as ***within-part*** *variation.*

In the short study, officially known as range method because it looks at the range (Max-Min) between two appraisers, two appraisers, A and B, will share the same gauge and the same parts (5 of them). Each appraiser, A and B, measure the parts only once. This study can be done quickly at any place.

Abbe's Principle

Many measuring gauges and nearly all production machines violate "Abbe's Principle", which is, simply stated, that the reading and measuring axes must remain coaxial for maximum accuracy. Many measuring instruments do not follow this rule: for example, all CMMs have their reading axis and measuring axis located far away from each other, violating this essential rule. The micrometer is a rare exception that follows Abbe's Principle.

Abbe's Principle: Micrometer vs. Caliper

Measuring and reading axes

Resolution: 0.001 mm (.00005 in)

Since screw thread is no longer the source of accuracy, 10 turns of the thimble cover 0-30 mm.

A miniature linear scale, or reading scale, is embedded on the axis of measurement. Measuring and reading axes are coaxial, thus meeting "Abbe's Principle" which is one of the fundamental rules of precision measurement.

Reading axis

Resolution: 0.02 mm (.001 in)

This distance between the reading and measuring axes violates "Abbe's Principle" where ideally the distance should be zero

The greater the distance between the two axes, the greater the potential error will be. This is one of the reasons why micrometers are 10 times more accurate than calipers.

Measuring axis

The workpiece should be placed closer to the main beam (broken line) where it will be measured more accurately.

Chapter 6

Surface Roughness

"A CRITICAL PARAMETER"

"Surface" is where one side of a product comes in contact with another. If it rotates as in the case of a shaft of a motor, the surface roughness must be specified. What is important here is the fact that the surface roughness is superimposed on the repetitive waviness, which in turn is superimposed on the form error. While these three elements cannot be separated, an attempt has been made for surface roughness to be isolated from the rest of geometric elements. Surface roughness is the smallest amplitude on the work surface left by the metal cutting or metal forming tools used in manufacturing.

Many components must possess a certain texture to perform required functions, such as the surface of white car body prior to painting, or the surfaces of journal bearings in crank and cam shafts. This chapter attempts to cover the basics of the surface roughness whose value is represented by "R" for Roughness, and most often expressed in terms of Roughness Average or Ra. More products today are specified with the surface roughness values and Ra is only the beginning.

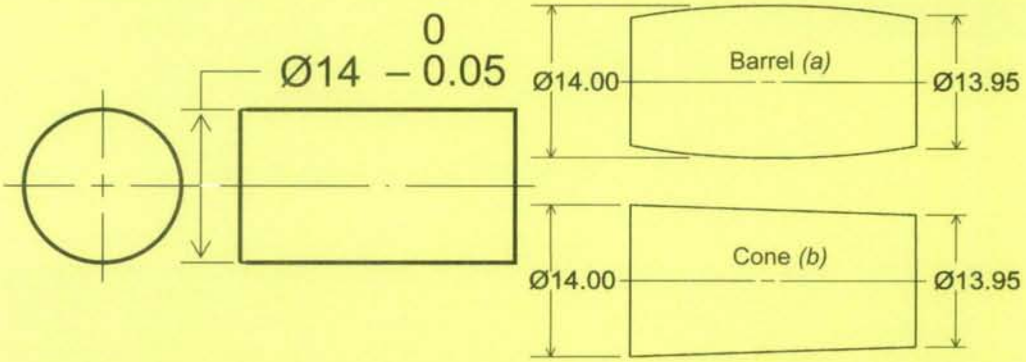
3 Steps of Dimensional Specifications

1 Limits of Size (typically specified with + / – to the basic dimension) Unit: mm

Both barrel *(a)* and cone *(b)* are within the limits of size.

Plus/minus from nominal size is only used here.

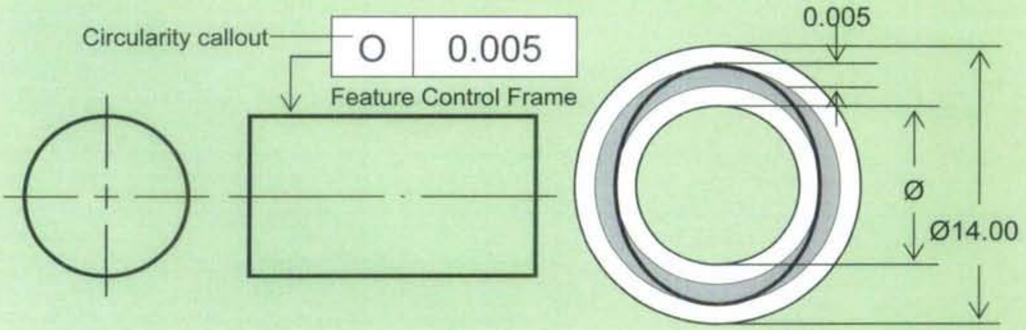
Zero cannot take polarity, so plus or minus sign is omitted.



2 Form or Form Error (specified with GD&T symbol, concept of "total zone" replaces +/-)

Flatness, Straightness, Circularity, and Cylindricity are known as Form.

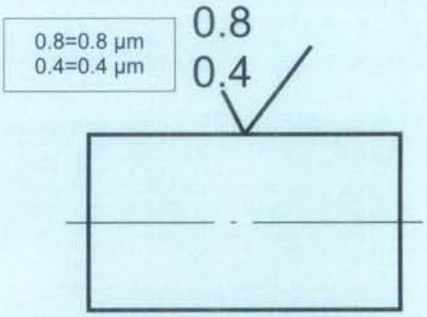
Circularity is based on the concept of "total zone": When a shaft is sliced normal to the axis, its cross-section must be round within 0.005 total wide.



3 Surface Roughness (parameters are often in Roughness average Ra but not always)

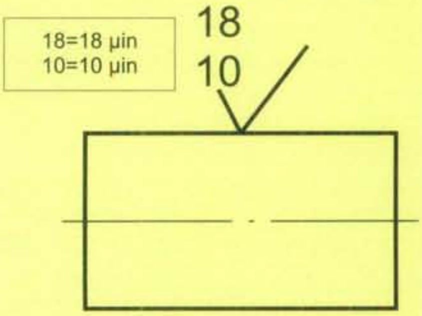
Surface Roughness value is to be specified with a roughness parameter, which is likely to be in Ra but it must be verified.

Metric Unit: micrometre



Roughness specifications are in µm

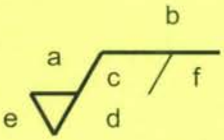
Inch Unit: microinch (µin)



Roughness specifications are in µin

Surface Texture Symbols [Source: ASME Y14.36M-1996]

Note: ASME Y14.36M is the engineering drawing standard written in M for metric. The American standard for Surface Texture is ASME B46.1



a	Roughness value stated here, often with upper and lower limits. The most popular parameter, Ra for Roughness Average, is no longer a default in recent prints.
b	Production method, treatment, coating, other text or note callout placed here.
c	Roughness cutoff or sampling length in millimetres, or in thousandths for inch system.
d	Direction of lay.
e	Minimum material removal requirement in millimetres, or in thousandth for inch system.
f	Roughness value other than Ra.

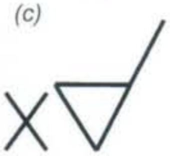
(a)

Basic surface texture symbol:
Surface may be produced by any method except when the bar or circle [symbol *(b)* or *(d)*] is specified.

(b)

Material removed by machining is required. The horizontal bar indicates material removal by machining is required to produce the surface and material must be provided for that purpose.

(c)



Material removal allowance in millimetres for "X" defines the minimum material removal requirement.

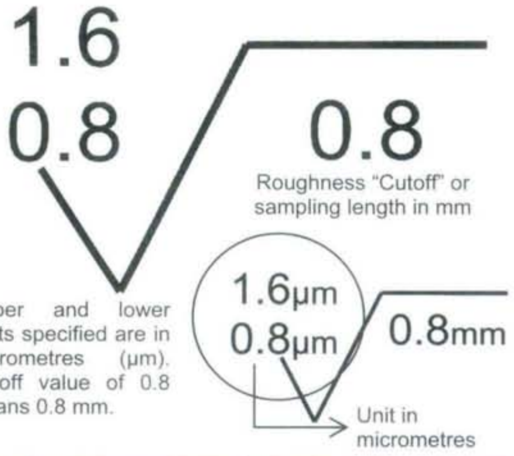
(d)

Material removal allowance. The circle in the Vee indicates the surface must be produced by processes such as casting, hot/cold finishing, forging, die casting, powder metallurgy or injection moulding without subsequent removal of material.

(e)

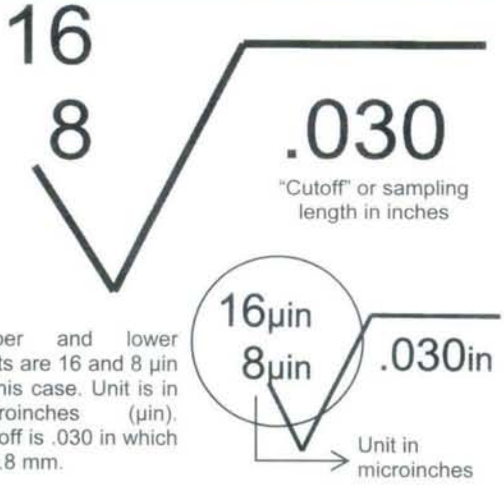
Surface Texture Symbol
To be used when any surface texture values, production method, treatment, coating or other text are specified above the horizontal line or to the right of the symbol. Surface may be produced by any method except when bar or circle [symbol *(b)* or *(d)*] is specified or when the method is specified above the horizontal line.

Metric Surface Roughness Specification



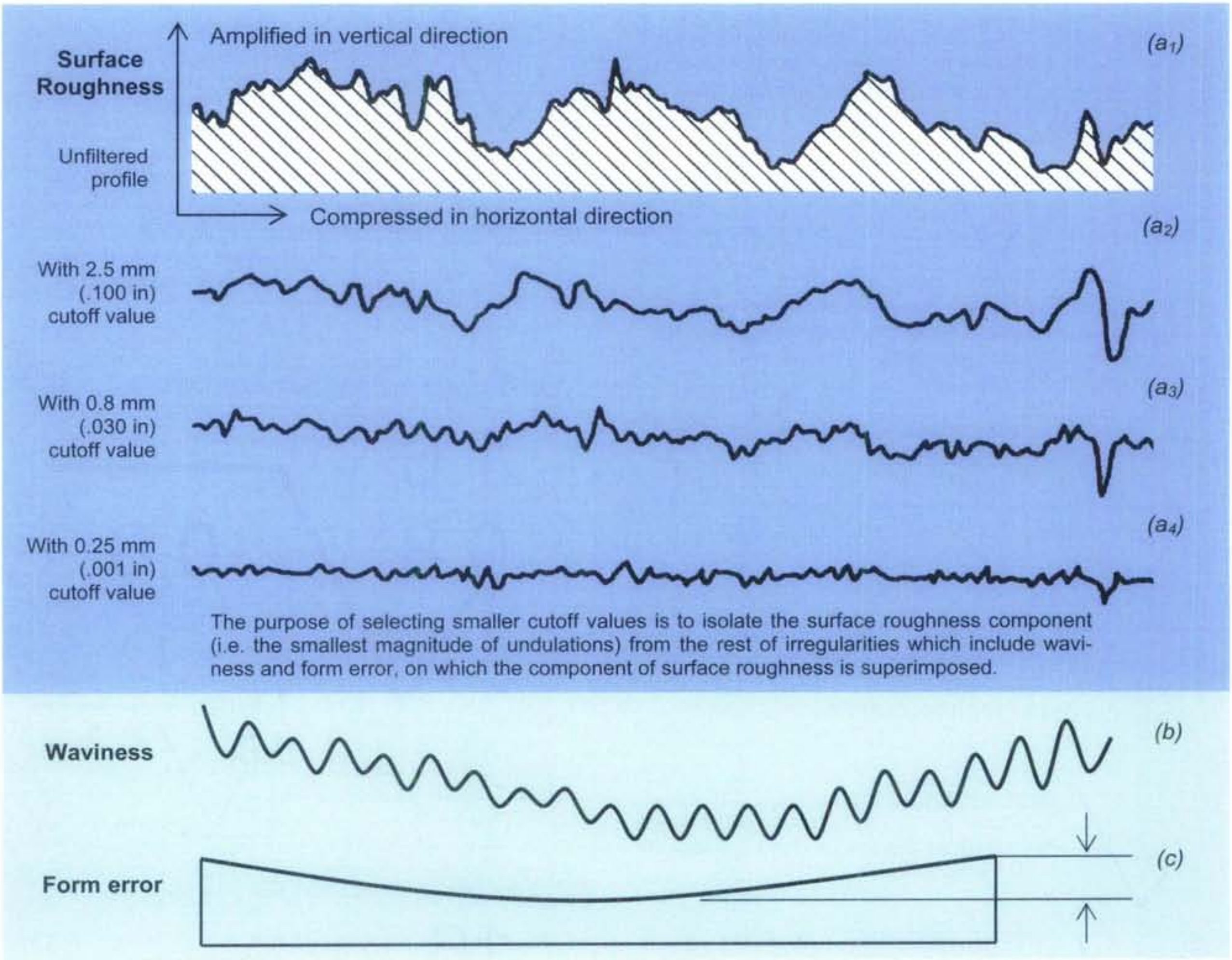
Upper and lower limits specified are in micrometres (µm). Cutoff value of 0.8 means 0.8 mm.

Inch Surface Roughness Specification



Upper and lower limits are 16 and 8 µin in this case. Unit is in microinches (µin). Cutoff is .030 in which is 0.8 mm.

Principles of Surface Roughness



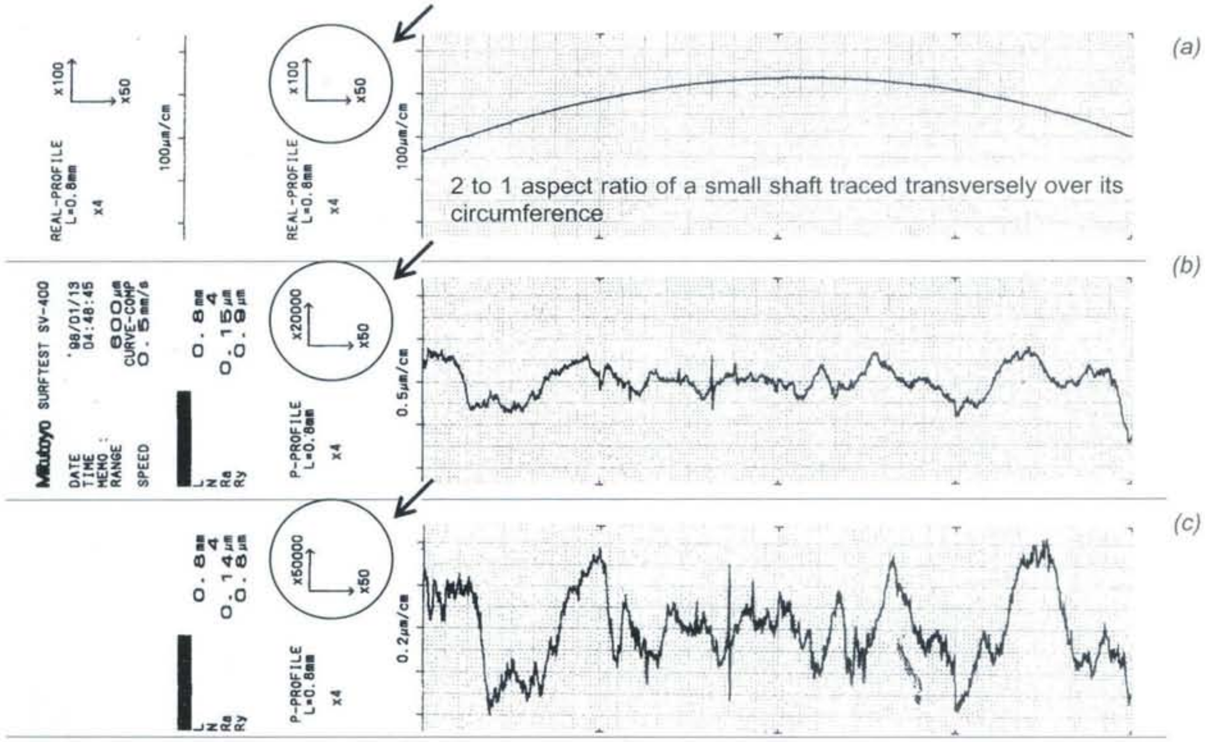
The purpose of selecting smaller cutoff values is to isolate the surface roughness component (i.e. the smallest magnitude of undulations) from the rest of irregularities which include waviness and form error, on which the component of surface roughness is superimposed.

Of the three components shown above, form, waviness, and surface roughness, the one with the smallest scale is the surface roughness parameter. In order to separate the surface roughness component from other elements, such as form and waviness, a filter is used to isolate the surface roughness element from the other elements which are larger in magnitude. Unfiltered profile *(a_1)* is a cross section of the actual part cut perpendicularly to the surface being studied.

Ra 250 µin Profiled | Ra 250 µin Shape Turn | Ra 500 µin Milled | Ra 500 µin Profiled

By applying a cutoff or filter, the profile changes its form from *(a_1)* to *(a_4)*. For this reason, the cutoff value must be agreed upon between the supplier and customer. In absence of such instruction, a cutoff value of 0.8 mm (.030 in) was typically chosen in the past. However, a cutoff of 0.8 mm is no longer a default, and must be validated since it will directly affect the resultant reading. As will be explained later in this chapter, surface roughness will be traced by a conical diamond-tipped stylus.

Reading the Hard Copy (Aspect Ratio)

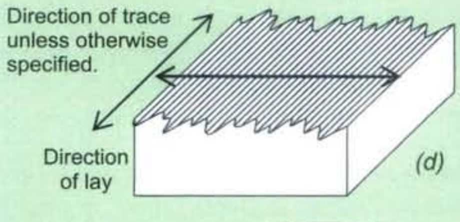


2 to 1 aspect ratio of a small shaft traced transversely over its circumference

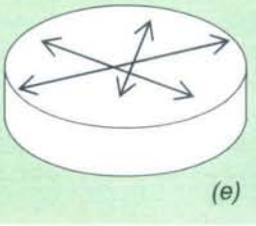
Aspect ratio (encircled) from top: 2 to 1 *(a)*, 400 to 1 *(b)*, and 1000 to 1 *(c)*

As evident from the first aspect ratio of 2 to 1 *(a)*, this curvature represents the circumference of a shaft traced across an axis. If traced along the axis of the length of the shaft, the surface roughness value would be much higher. The tracing cutoff was 0.8 mm (.030 in), which is the most common cutoff value. The tester was instructed to sample 4 times of 0.8 mm in this example, although 5 times of the value of cutoff is more popular. The concept behind this is that the total 3.2 mm (0.8 x 4) length should be long enough for evaluation. The "cut off" is a term used by many but "sampling length" is more official, and it is also known by a Greek letter λ (lambda) or λc.

The hardcopy of surface roughness is always compressed in the horizontal direction. It makes a better sense to summarise the undulation *I* this way. If magnified without horizontal compression, it would require a very long piece of paper to cover the entire magnified surface. See example *(c)* above: The aspect ratio is 1000 to 1, or 50000X by 50X. Imagine how wide this page would be if the ratio is 1 to 1. This compression does not affect the overall result, since inspectors are more interested in the peaks and valleys produced.



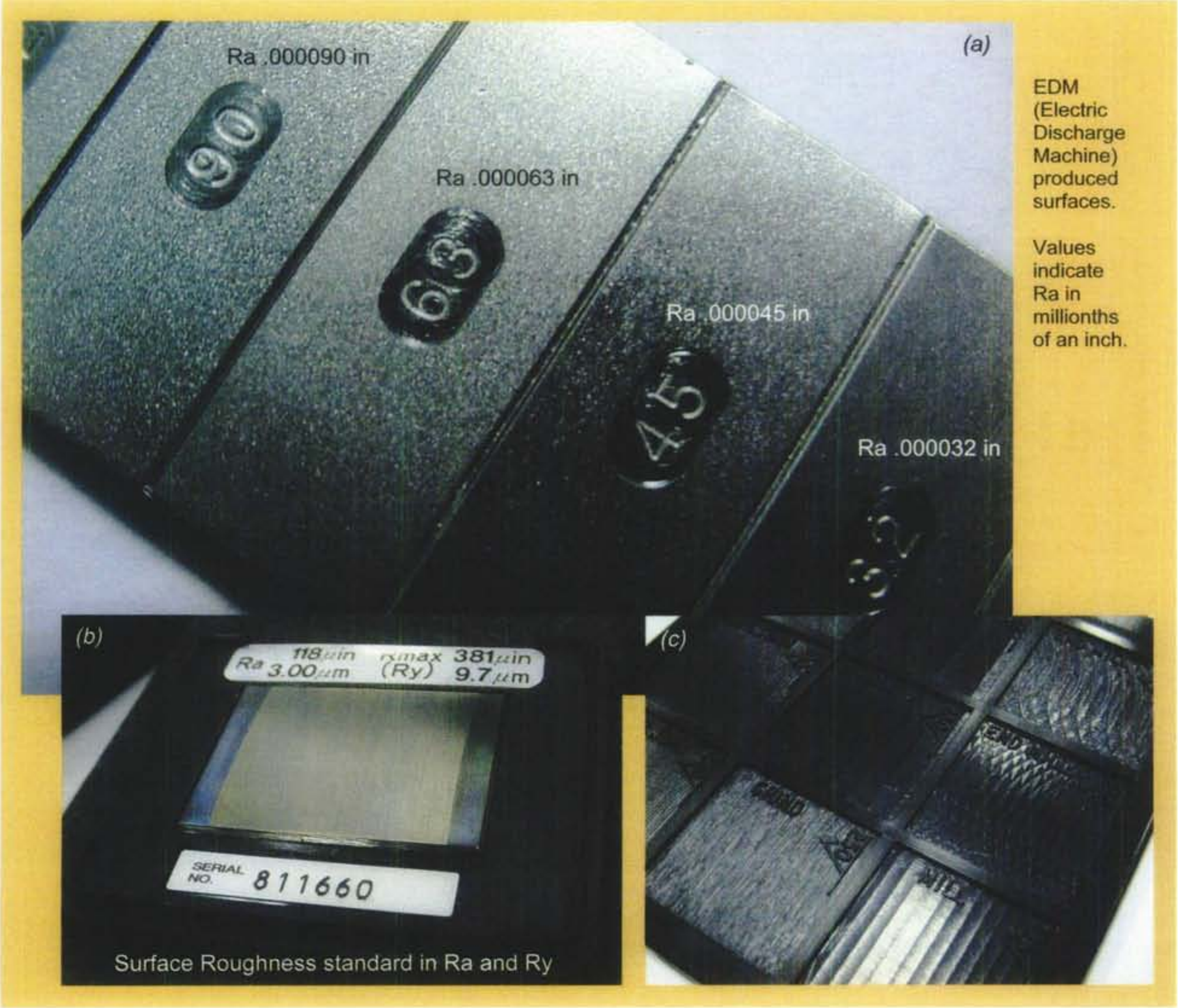
When there is no apparent lay on the surface *(e)*, trace it into several directions and pick up the largest roughness value. On the other hand, when the direction of lay is clear *(d)* go against it to pick up the largest value.



Absence of lay examples: workpieces made by injection moulding, powder metrology (PM), investment casting, etc.

Often the specifications on the prints are maximum value, meaning the upper limit of surface, and workpiece must be below the specified value.

Surface Roughness Comparators



EDM (Electric Discharge Machine) produced surfaces.

Values indicate Ra in millionths of an inch.

Surface Roughness standard in Ra and Ry

In inch system, "90" means Roughness Average (Ra) of .000090 in. All references are indicated in Ra and in the unit in millionths of an inch. In metric, the number in surface roughness specification is in micrometres (microns), but often in sub-microns. Example: 0.7 means 0.7 micrometres (0.7 µm).

The sandy looking surface finishes shown above *(a)* are made by the EDM (Electric Discharge Machine), which evolved into a major branch in machining technology with the introduction of the Wire EDM in the 1970s. Some people affectionately call them "look-up charts." These replicas represent a visual guide for surface finishes and are useful tools to have. However, this handy look-up chart is not a standard.

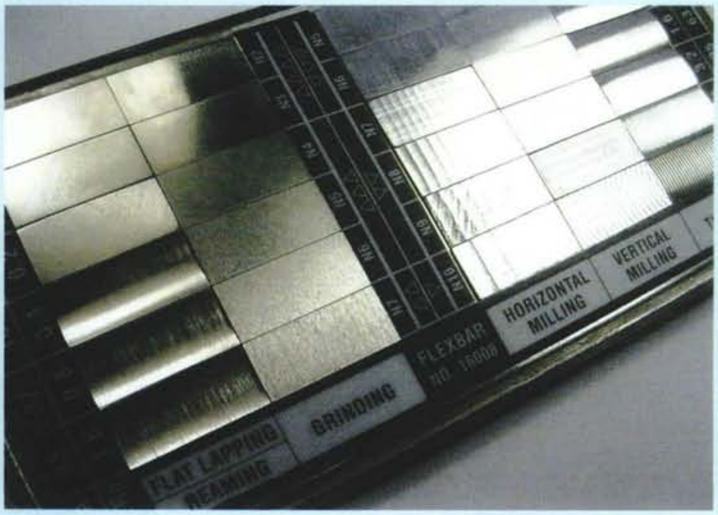
Standards are identified by a unique serial number *(b)* for traceability. It is important to know what the different types of standards such as *(b)* to differentiate them on sight from references or replicas like *(a)* and *(c)*.

Unless someone brings in a couple of samples and shows everyone what a 0.2 µm (8 µin) finish looks like, it would be hard to realise such a finish (a very smooth mirror-like surface). Known as "roughness comparators" these are nickel-based, electroformed samples ideal for any metalworking operation. They are inexpensive and highly effective aid to have, although they are not standards.

The differences between the standard and these examples are subtle: Both look alike, however only one is supplied with a certificate and serial number for traceability. Some are already tested with multiple traces on the patch. For those who are in plastic industry, they also offer plastic plates with a variety of surface finishes (previous page *(c)*). The numbers and names assigned are unique to that industry.

Ra µm	Ra µin
6,3	250
3,2	125
1,6	63
0,8	32
0,4	16
0,2	8
0,1	4
0,05	2
0,025	1

Typical roughness numbers selected for roughness comparator charts

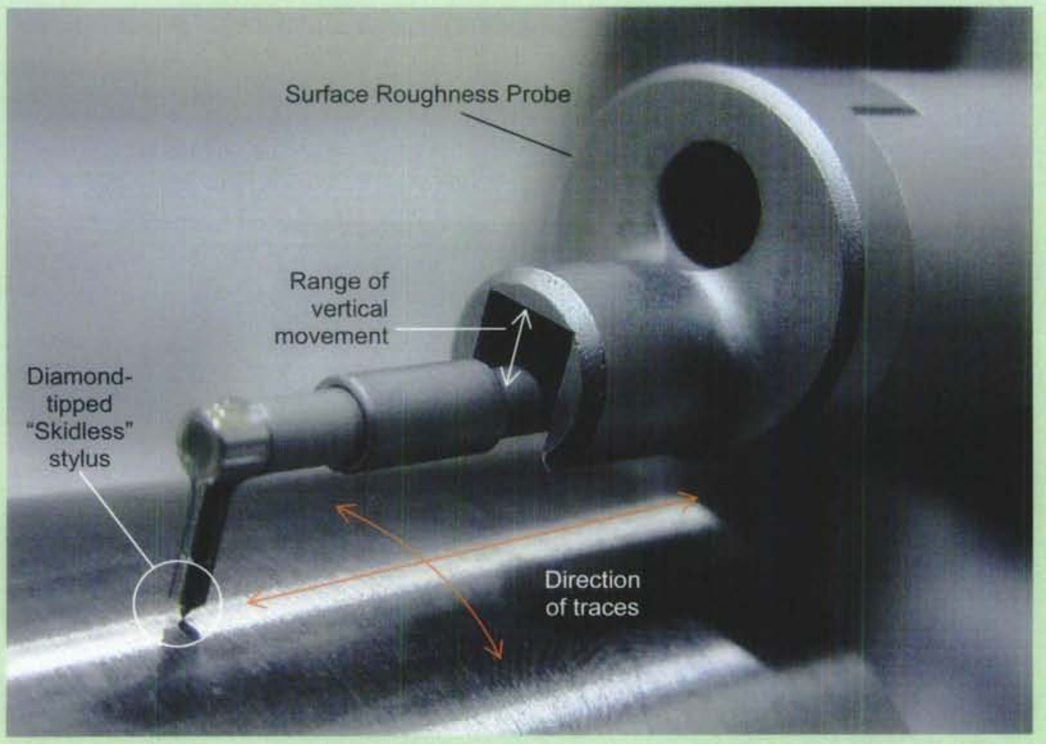


These reference plates are known as "roughness comparators" or in some cases they are called "look-up charts." The key word is that they are visual comparators and are not standards. Within this limitation, they serve as excellent visual aids to see what Ra 250 really look like under milling, or EDM, or any other metal-cutting or forming operations.

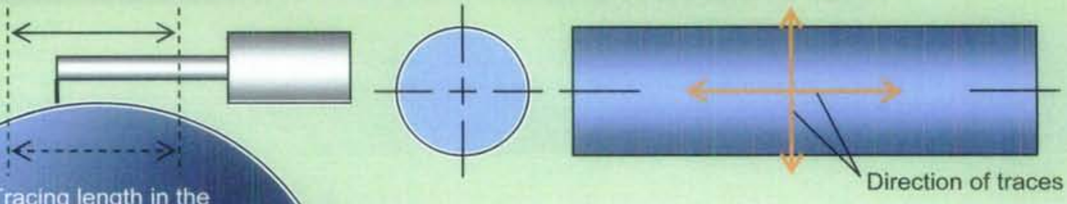
The roughness numbers selected for these charts are predetermined as shown in the table (above).

Unless otherwise indicated, all numbers are in Ra, the most popular parameter in roughness.

Determining Roughness by Probing



A modern roughness tester such as this one has the ability to trace in two different directions



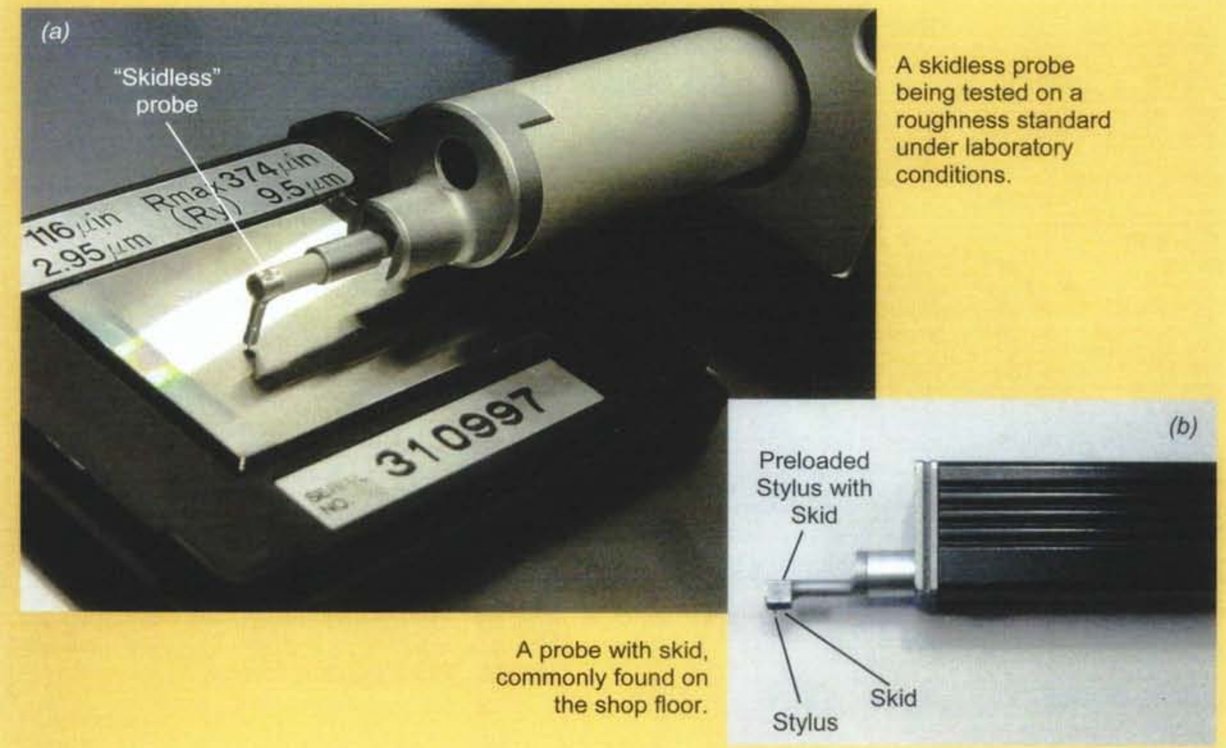
Tracing length in the circumferential direction may be limited by the length and vertical moving range of the stylus. In most cases, a small sample tested circumferentially should be enough to estimate the surface roughness of the entire area. Flip the specimen over and test other areas as well. The reading may be the same.

Due to the curvature, the length tested will be limited. To overcome the lack of area traced, this part should be rotated and opposite side must also be measured. It is highly likely that the other side will have the same roughness value.

Most standard surface roughness testers are designed to trace flat surfaces or cylindrical surfaces, internal and external, in the axial direction. Some recent models, such as the one shown above, can trace two directions: against the lay as usual and along the lay. If a cylindrical part rotates, the surface roughness in the entire circumferential direction may be of importance. Unless otherwise specified, to trace against the lay is the default.

A large number of recently introduced surface roughness testers offer this capability as shown on this page. The measuring range is limited only by the physical length of the probe selected. In this example, demonstrated above, the probe is much longer than the standard size. The surface traced by the diamond tip can be magnified as much as 50,000 times in vertical direction.

Skid and Skidless Probes



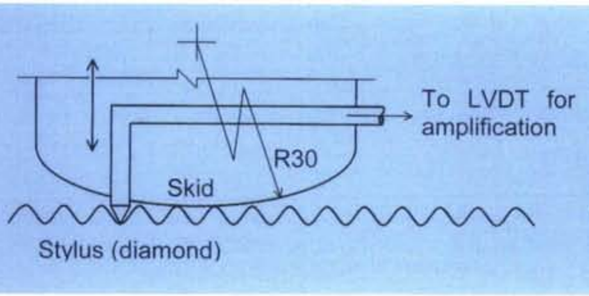
A skidless probe being tested on a roughness standard under laboratory conditions.

A probe with skid, commonly found on the shop floor.

All hand-held type surface roughness testers are featured with a diamond stylus supported by a skid. The unit above, *(b)*, is a typical example. This design allows the stylus to move in the direction of amplitude but is restricted by the presence of a skid. Often, the entire probe is preloaded to make a positive contact with the surface feature, making it possible to work upside down, if needed.

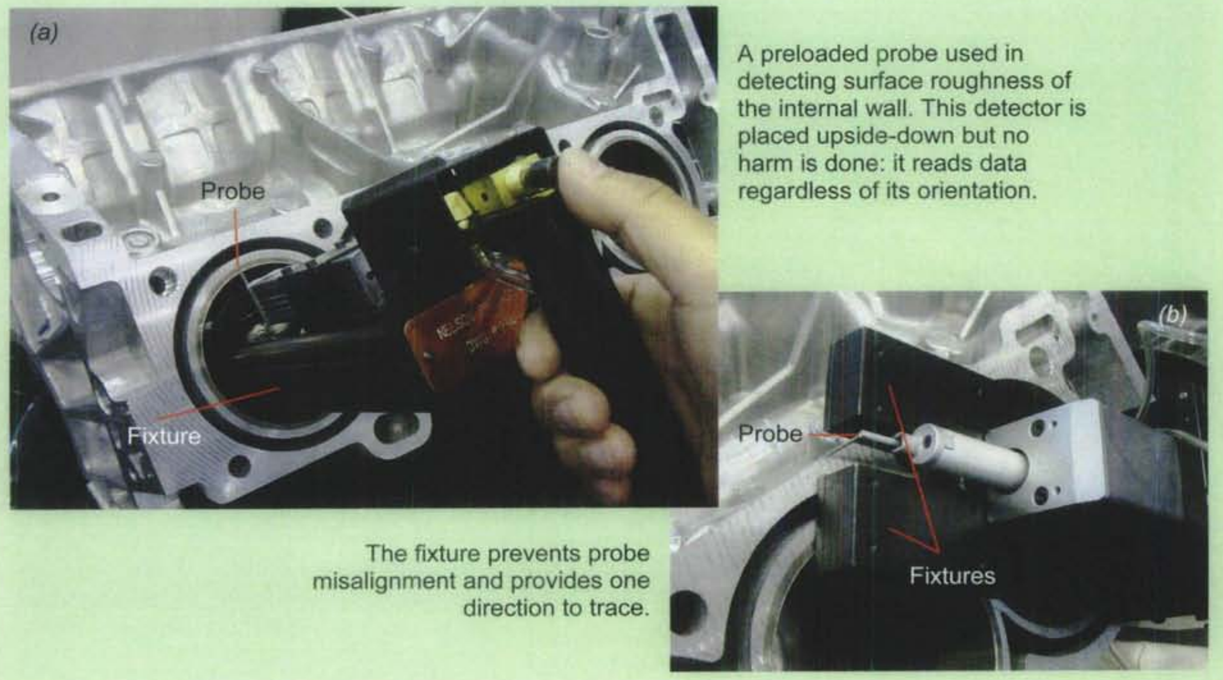
As its name suggests, the so called "skidless" probe is without a skid and is directly connected to a driver that moves the stylus horizontally.

"Skidless" type *(a)* is typically used in a laboratory where vibrations are minimised. Many surface roughness parameters are in the sub-micron level: minute vibrations will be picked up by the stylus and thus affect the reading. The portable type *(b)* with skid at right, on the other hand, is for the production floor. The unit with skid is more robust in daily operations.



As this drawing indicates, the stylus is supported by the so called "skid." Large-scale undulations will be mechanically filtered out by the skid, and thus the surface roughness component will be isolated.

Using Dedicated Fixtures for Better Gauge R&R



A preloaded probe used in detecting surface roughness of the internal wall. This detector is placed upside-down but no harm is done: it reads data regardless of its orientation.

The fixture prevents probe misalignment and provides one direction to trace.

Surface roughness values specified on blueprints are the smallest of all dimensional specifications; anything smaller than surface roughness simply does not exist in the metalworking industry. Surface roughness specifications are often below micron level (μm) or in millionths of an inch (μin). Because of this, the resultant reading with a diamond stylus may vary from one operator to another if the instrument is casually operated. Fixtures, as shown here, help minimise that bias.

The detector is wrapped around by special fixtures, shown in *(a)* and *(b)*, restricting its movements to one direction. The traced paths relative to the work surface will thus remain consistently parallel to the bore axis in *(a)* thus producing far smaller (i.e. better) Gauge R&R.

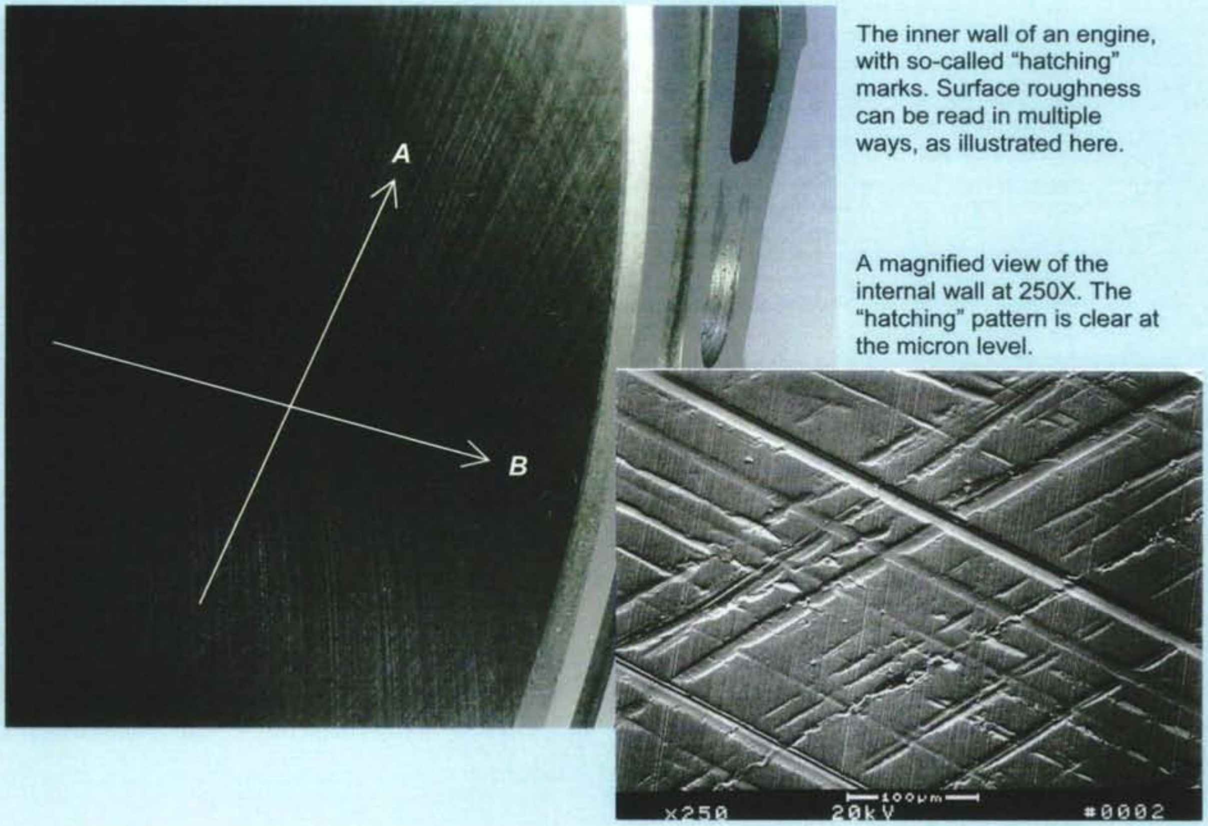
Large Gauge R&R comes from a larger variation in tracing orientation, from one operator to another, or from one shift to the next. If this could be removed, then the Repeatability & Reproducibity should become much smaller.

The top land of the engine block where the cylinder head will be seated is called the "top deck", where a gasket will be inserted *(b)*. It is face-milled, but must retain a texture to accept the gasket. Surface roughness is specified on the top deck for this reason.

As demonstrated in taking the roughness value of the cylinder's internal wall *(a)*, the fixture allows only one set direction to trace, parallel to the axis, thereby minimising personal bias, also known as Reproducibility or Appraiser Variance (AV).

Thus anyone can use the fixture and insert it into the cylinder bore, since this fixture locks the orientation of trace. Simply clicking the start button will initiate the automatic testing.

Detecting Surface Roughness



The inner wall of an engine, with so-called "hatching" marks. Surface roughness can be read in multiple ways, as illustrated here.

A magnified view of the internal wall at 250X. The "hatching" pattern is clear at the micron level.

Surface Texture is a broader term assigned to cover the entire characteristics of the surface area, of which *Surface Roughness* plays a major role. To detect the roughness value in sub-microns (or microinches), a contact method with diamond-tipped stylus is commonly used. It will be clear from the above example that the internal wall of an engine block is not mirror-finished. Instead, a texture called a "hatching" pattern is produced on the surface.

Pistons are typically featured with a couple of thin C-shaped rings that come in contact with the wall. A mirror-finished wall is not called for; the internal wall must have a texture to retain oil molecules on its surface to lubricate the fast-moving piston rings. The enlarged wall surface at 250X reveals the true texture.

To check the surface roughness, a probe will be inserted and it will trace on the surface finish. It is conceivable if probe traces in two directions *A* and *B,* as illustrated above, the resultant readings may be different. If the direction of trace is undefined and inspectors are free to choose, Gauge Repeatability & Reproducibility (or simply R&R) may suffer.

In view of this condition, the fixture introduced on the facing page, where the direction of trace is predetermined, starts to make sense. One trace after another it will trace in line with the axis of the bore, thus improving Gauge R&R. Since the entire operation is highly automated, the parameter selected is often Rpk rather than Ra.

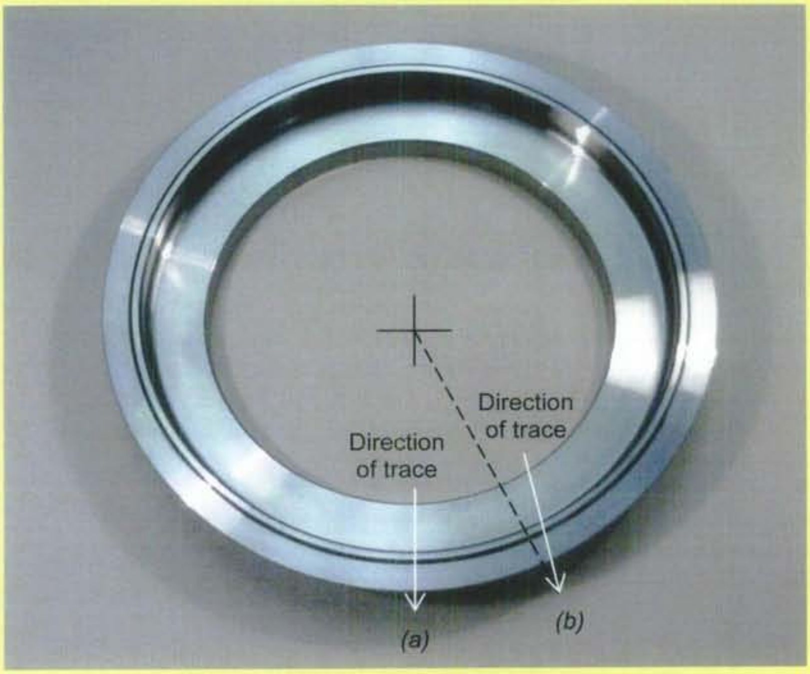
Surface Roughness Facts to Remember

Let's review the meaning of numbers attached to the surface roughness specification. Try 0.7 for example. Assume the parameter to be Ra 0.7. In inch blueprints, the numbers for surface finish are always specified in terms of millionths. Example: "18" in inch system means 18 millionths (.000018 in). Sizes below one millionth (e.g. 0.7) do not exist in the inch system. Therefore, 0.7 must be a metric number.

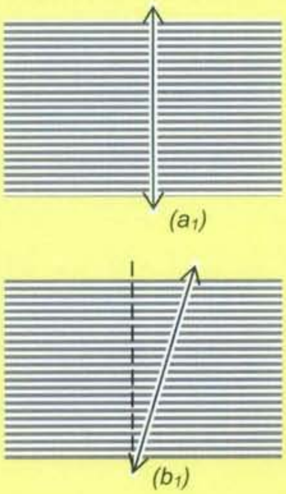
What if the data turned out to be Ra 0.8, instead of 0.7? Do we reject it, since it exceeded the upper limit by 0.1 µm (.00004 in)? This is where supplier and customer may disagree, since the unit is extremely small, often in sub-microns (metric) or in millionths (inch).

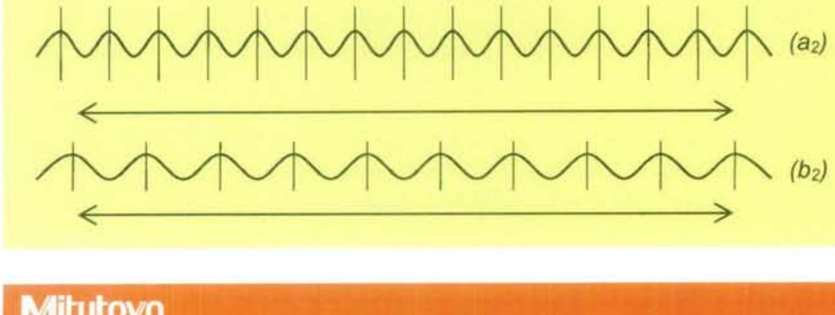
It has been a practice of the industry to specify only the upper limit for surface roughness and leave the lower limit open. The assumption here is that the finish must be better than the upper limit value. After using a probe to test, the largest surface roughness number should be checked. When Roughness average (Ra) is not effective, other methods may be used. Peak Count (PC), introduced below, is one such example.

The Difference between Ra and PC



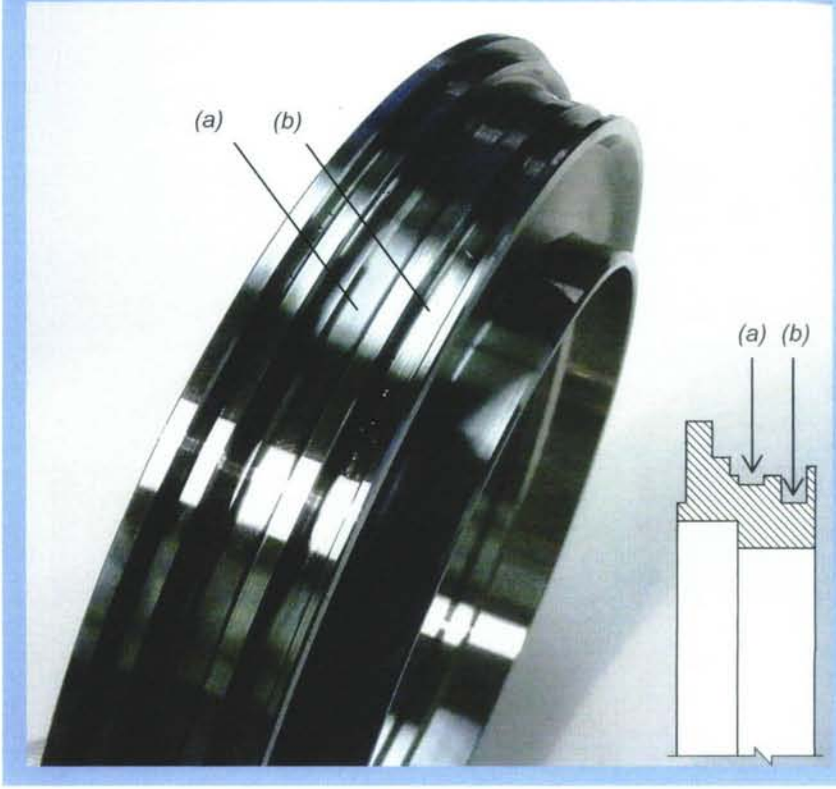
Assume that this ring at left has been traced in the 2 directions *(a)* and *(b)*. Since the surface has concentric rings etched on it, the traces are as follows:





When the peak heights and valley depths are analysed by Roughness average (Ra) method, both *(a_2)* and *(b_2)* may share the same Ra value. However, if peaks are counted by a method called Peak Count (PC) the result will be different.

Cutoff Lengths



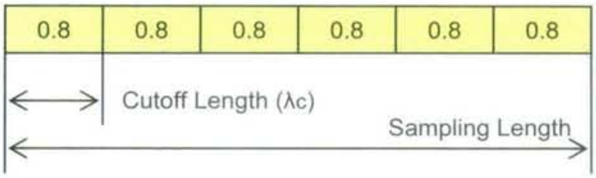
For extremely narrow areas such as this example *(a)* and *(b)*, the standard probe with skid will not reach the surface in question. A longer stylus and skidless probe will be required.

Once the stylus touches the surface, the rest is easy. When the horizontal land is restricted as in the areas *(a)* and *(b)*, the sampling length should also be restricted. The standard approach is 0.8 x 5 (4 mm in total) but there's simply not enough land to touch.

In real life nothing seems as simple; what was explained in the textbook may or may not be obvious on the shop floor. Here is another case where the standard probe with skid will not work: In example *(a)*, the probe with skid is useless since it is too wide to fit between the lands. The stylus must be long enough to touch the narrow land where probe movement is otherwise restricted. For this reason, a variety of probe and stylus combinations are offered to solve this problem.

The most common Cutoff Length is 0.8 mm (.030 in), with probe lengths that are five times of this Cutoff value, making the Sampling Length 4 mm (.150 in). When it is too narrow, the Sampling Length can be switched to a smaller value (changing the roughness reading) and Sampling Length can be less than five times under this restricted condition.

When the probe movement is limited, there are two choices: (1) select a narrower Cutoff Length and/or (2) reduce Sampling Length. If this is done, the customer must be notified so that the two parties understand the predetermined conditions.



Common Cutoff Lengths in metric

Unit: mm

0.02	0.08	0.25	0.8	2.5	8	25

Common Cutoff Lengths in inch

Unit: Inch

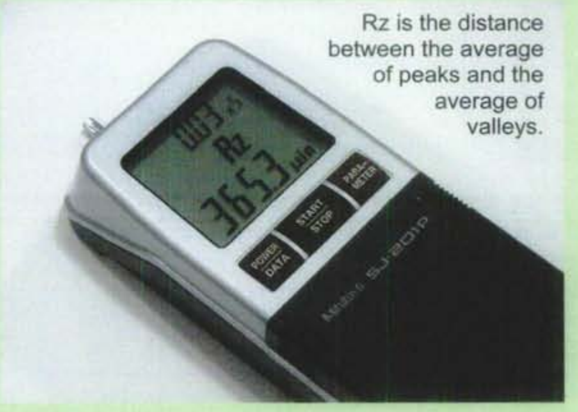
.001	.003	.010	.030	.100	.300	1

Ra, Rq, Ry, Rz

RMS (Rq) was used in US more than in any other nation: When surface roughness measurement technology debuted in the US, surface undulations were calculated in terms of RMS to get average roughness. Later on, the old RMS was renamed as Rq. Ra and Rq are very close as evident in the table below. Rq is however always greater than Ra, and in this particular case Rq is 10% greater than the Ra value. Conversion between the two is not recommended because it may be more than 10%.

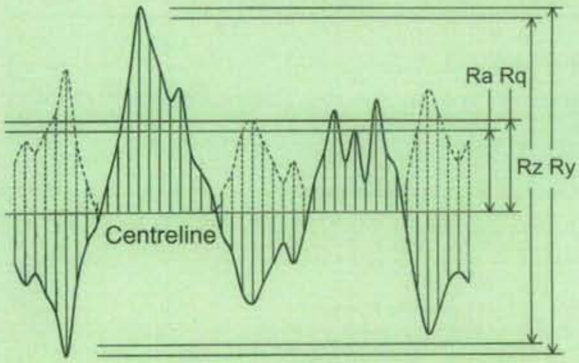
Ra is now the most commonly specified roughness parameter.

Rq was known as RMS. Rq reading is, in this case, about 10% higher than Ra.



Rz is the distance between the average of peaks and the average of valleys.

Ry is the largest of the four readings. Ry is max-minus-min reading within the evaluation length.



Here are the four common surface roughness parameters. As can be seen from the table below and the graph at left, Ra < Rq < Rz < Ry.

From one trace, 4 parameters or more	
Parameter	Ratio against Ra
Ra = 116.4 µin	1
Rq = 128.7 µin	1.1 times greater
Rz = 365.3 µin	3.1 times greater
Ry = 375.2 µin	3.2 times greater

Chapter 7 Hardness Testing

"THE INDENTATION METHOD"

Hardness of a metal is usually considered as "the resistance to permanent indentation". To judge how hard the metal in question is, an indenter is pressed into the surface of metal under a specific load for a definite a definite time interval, and the hardness number is then derived from the area indented (Vickers and Brinell), or the depth of indentation (Rockwell and Superficial Rockwell).

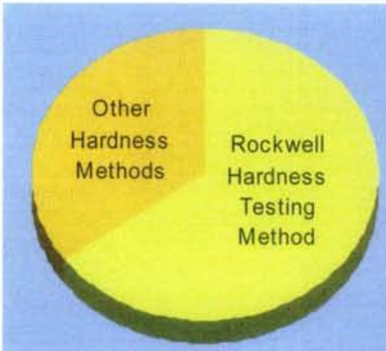
Many methods of applying load and quantifying the resistance to deformation have been suggested, and are used in the industry.

The hardness scales most commonly used today are:

- Brinell Hardness (J. Brinell, 1900)
- Vickers Hardness (R. Smith/G. Sandland, 1925)
- Rockwell Hardness (S. Rockwell, 1919)
- Rockwell Superficial Hardness (S. Rockwell, 1921)
- Shore Hardness (A. Shore, 1907)
- Knoop Hardness (F. Knoop, 1939)

The internationally standardised (ISO) hardness scales are: Brinell, Vickers, Rockwell (including Superficial) hardness. Of these, the Rockwell Hardness scale is probably the most popular of all, with the Rockwell C-Scale (HRC) specifically appearing to be a majority.

Like many other mechanical characteristics, hardness is a relative value that has no fundamental quantity of absolute standard, which is rather different from physical quantities such as precise length. In reality, hardness is often used as a substitute measure to determine other physical characteristics.



Of all the hardness testing methods in use today, the Rockwell hardness is by far the most popular. Of all the alphabets used in Rockwell, the C-Scale, officially HRC for "Hardness Rockwell C", is the most used of all Rockwell testing methods.

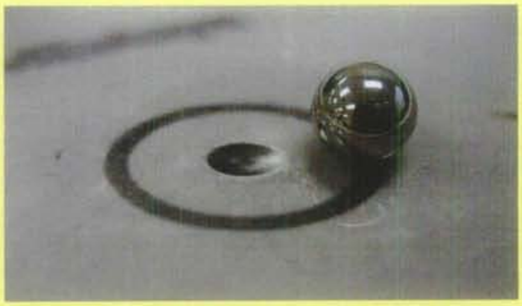
The Concept of Hardness

Hardness is usually defined as the resistance of the test specimen to permanent indentation. Hardness is not a fundamental property of materials and, as such, hardness numbers are arbitrary rather than absolute in nature. If this statement is true, why is hardness testing so universally applied? The answer may lie in two aspects of hardness testing:

(1) Such tests are relatively easy to perform, and are relatively non-destructive.
(2) Hardness testing correlates well, if not precisely, with other physical properties of such materials.

Thus the hardness test is a simple and non-destructive method of determining the suitability of a material for its intended use. Some of the factors that relate with hardness are:

- **Ability to resist indentation:** As one would expect, the ability of parts such as escapement parts are subject to indentational forces that can be correlated directly with indentation-type hardness testing methods. The most common application is predicting the ability of bearing races to resist so called "Brinelling", which is indentation from ball bearings upon impact.
- **Abrasion Resistance:** Mohs hardness numbers, 0 to 10, 10 being the hardest (diamond), which corresponds roughly to logarithmic values of indentation hardness. The ability of parts to resist abrasive wear shows a similar relationship, in which a large increase in indentation hardness corresponds to a lesser increase in scratch and abrasion resistance.
- **Yield Strength:** The correlation between hardness and yield strength is positive and significant, but it varies sharply from a straight-line relationship for metals that have been treated for increased hardness.
- **Impact Strength:** Within a specific alloy or metal type, impact strengths are inversely related to hardness (i.e. harder metals are more brittle). This does not apply in comparing one type of metal with another. There is no direct correspondence between impact strength and indentation hardness, except when comparing materials of the same alloy.
- **Malleability and Ductility:** These properties are generally inversely related to hardness. As with impact strength, comparisons can only be made with materials of the same alloy or formulation.



In 1900, Brinell's idea to indent a SØ 10 mm steel ball into the specimen under a static load as high as 3000 Kg was the beginning of modern hardness testing methods. This is called indentation method. Others such as Rockwell, Vickers, and Knoop also fall into this category.

The indentation hardness testing such as Rockwell is by far the most popular in industry because of its simplicity. However, this does not preclude other testing methods like:

- **Static Indentation Test:** a ball, diamond cone or pyramid is forced into the surface of the material being tested. The relationship of load to the indented surface area (Vickers and Brinell) or the depth (Rockwell) of indentation is the measure of hardness.
- **Rebound Test:** an object of standard mass and dimension is bounced from the surface of the workpiece being tested, and the height of rebound is the measure of hardness. While primitive in approach, this method may be desirable when a test specimen is too large or too heavy to move.

The US standard: ASTM E-18

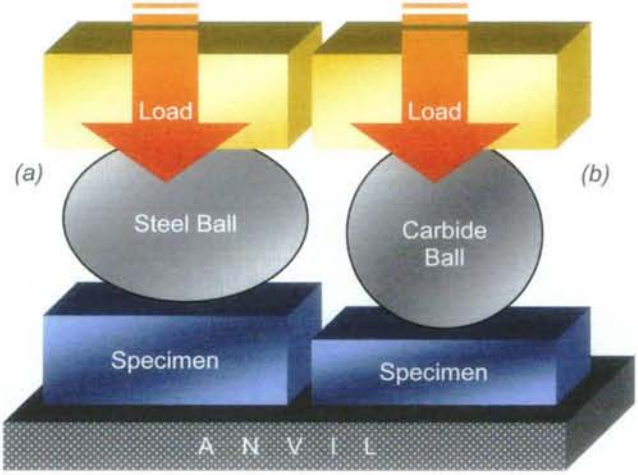
The steel ball indenter *(a)* has always been used in Rockwell hardness from Ø1/16 to Ø1/2 inch in size until recently. Under the ASTM E18-02, tungsten-carbide balls are also allowed in Rockwell hardness testing. This is the first step forward to a planned conversion from steel balls to tungsten-carbide balls.

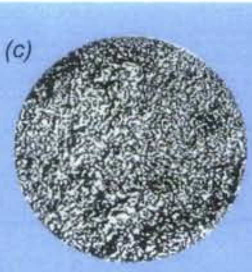
Pressured by the prescribed load, a Ø10 mm steel ball under Brinell hardness testing will penetrate into the test specimen. During this process the steel ball may flatten under pressure as illustrated at right *(a)*. A flattened ball will penetrate less than a round ball under the same load, thus creating a false impression that the specimen is harder than what it really is. In the case of Rockwell, it is the depth of the indent from which Rockwell derives its number: the deeper the depth of ball penetrated, the softer the material should be.

Ultimately the ball indenter using steel balls will be changed over to tungsten-carbide balls. In the meanwhile, in order to alleviate the confusion during this transitional period, ASTM E18-02 standard suggests that "S" for steel ball and "W" for tungsten-carbide ball be added to the number:

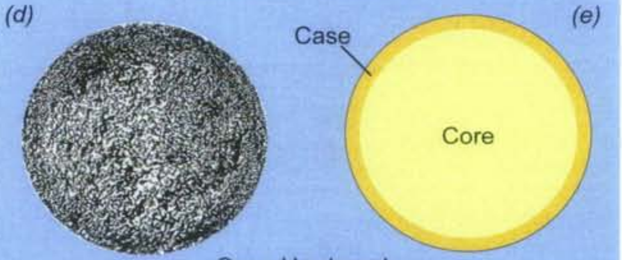
80HRBW
(80 Hardness Rockwell B-Scale Carbide Ball)

The difference between the past practice of using steel balls and the proposed new method of carbide balls is, depending upon various conditions, up to one hardness number in the case of B-Scale; that is to say the carbide ball will penetrate as much as 0.002 mm deeper than its steel counterpart.





Non Case-Hardened



Case-Hardened

In case-hardened products, such as example *(d)* and *(e)*, two different hardness numbers coexist in one product: a much harder shell-like outside, and a relatively softer inside which is to absorb distortional forces. A bevel gear shown at left may be a good example. It will be faced with another gear, and by doing so transfer the rotation of a shaft from one axis to another. What is so-called "core" in Rockwell hardness is still being debated. No single hardness number can separate the case from the core. The consensus is: the area below 50 HRC (50 Hardness Rockwell C-Scale) is said to be the core.

Rockwell Hardness Testing

Rockwell hardness testing is, by far, the most often used method for determining hardness. Here are some of the reasons why Rockwell is so popular and widely used in industry:

(1) Rockwell hardness test is relatively simple to perform and does not require skilled operators. Moreover, the current Rockwell tester is fully automatic and what is required is to push a button and stay away. The rest is done by the machine.

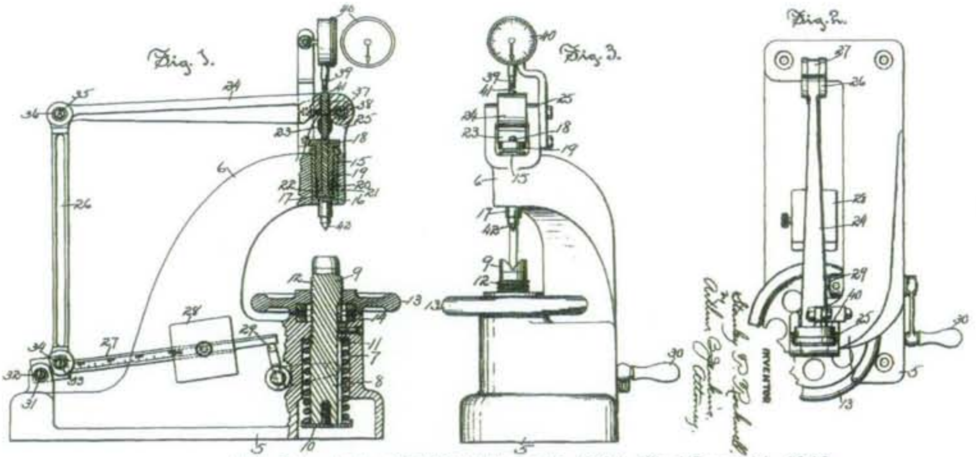
(2) By selecting a different load and indenter, Rockwell hardness can be used to determine the hardness of most metals, ranging from soft bearing materials to hardest steels. The reason why Rockwell number cannot exceed 100 is due to its dial indicator. Most of which at the time of his filing the patent in 1919 could read from 0 up to 100 in one revolution. If Rockwell wanted to read 200 or 300 in hardness, he simply changed the dead weight so that the resultant reading will fall within 0 to 100.

Rockwell Hardness Tester (Regular type)	
Superficial Rockwell Hardness Tester	
Preliminary Force (Minor Load)	
Rockwell (Regular)	Superficial Rockwell
10 Kgf	3 Kgf
Total Force (Major Load)	
Rockwell (Regular)	Superficial Rockwell
60, 100, 150 Kgf	15, 30, 45 Kgf

(3) Hardness number reading can be taken in a matter of seconds with conventional manual models and even less time with automated setups which provide much more consistent results.

(4) More elaborate preparation and measurement via optics as in Vickers are not required; all readings are direct reading of the depth indented.

The Rockwell Hardness Tester

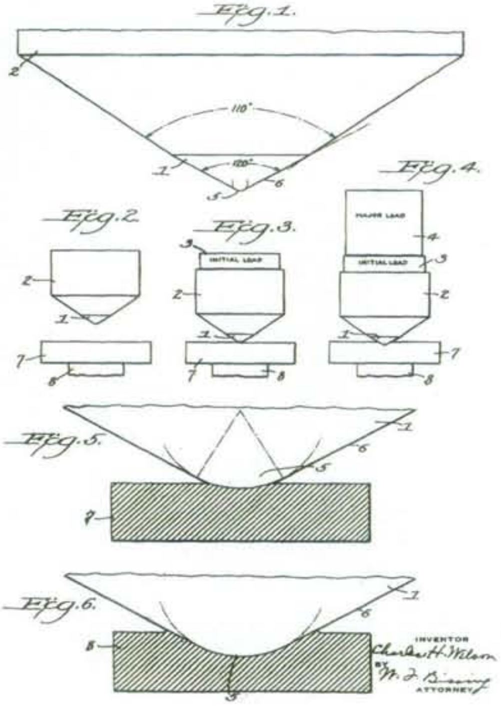


U.S. Patent No. 1,516,207 Nov. 18, 1924 Filed Sept. 11, 1919

The patent shown here was filed in 1919, a year after WWI. It may not be entirely unrelated to World War I where airplanes emerged for the first time as strategic military equipment. All of them used propellers that required ball bearings.

It was from these ball bearings, to a large extent, from where the interest in hardness started. Failure of ball bearings under load in the airplane could have been the starting point for Stanley P. Rockwell, who had been working in a ball-bearing manufacturing plant in Connecticut. He needed to know the hardness of ball races quickly and more accurately. Soon, his business partner, Charles H. Wilson, expanded on Rockwell's design and helped advance the Rockwell hardness test into one of the most recognised of all laboratory tests today.

Charles H. Wilson's Diamond Indenter



The diamond indenter for hardness testing machines was proposed by C.H. Wilson in 1924. The document at left is his patent 1,571.310 granted on February 2, 1926. The included angle of the diamond was 120°, and its nose was made spherical (SR 0.2 mm) to avoid damage under extreme pressure. The diamond indenters are allowed to have ±1° error from nominal 120°. Many indenters are supplied with matching hardness standards to compensate for some of the irregularities found in virgin diamonds.

Regular Rockwell Hardness Scale			
Scale	Indenter	Minor and Major Load	
B	Ball Ø1/16 in	10 Kgf	100 Kgf
C	Diamond (Brale)	10 Kgf	150 Kgf
A	Diamond (Brale)	10 Kgf	60 Kgf
D	Diamond (Brale)	10 Kgf	100 Kgf
E	Ball Ø1/8 in	10 Kgf	100 Kgf
F	Ball Ø1/16 in	10 Kgf	60 Kgf
G	Ball Ø1/16 in	10 Kgf	150 Kgf
H	Ball Ø1/8 in	10 Kgf	60 Kgf
K	Ball Ø1/8 in	10 Kgf	150 Kgf
L	Ball Ø1/4 in	10 Kgf	60 Kgf
M	Ball Ø1/4 in	10 Kgf	100 Kgf
P	Ball Ø1/4 in	10 Kgf	150 Kgf
R	Ball Ø1/2 in	10 Kgf	60 Kgf
S	Ball Ø1/2 in	10 Kgf	100 Kgf
V	Ball Ø1/2 in	10 Kgf	150 Kgf

Superficial Rockwell Hardness Scale			
Scale	Indenter	Minor and Major Load	
15N	Diamond (N Brale)	3 Kgf	15 Kgf
30N	Diamond (N Brale)	3 Kgf	30 Kgf
45N	Diamond (N Brale)	3 Kgf	45 Kgf
15T	Ball Ø1/16 in	3 Kgf	15 Kgf
30T	Ball Ø1/16 in	3 Kgf	30 Kgf
45T	Ball Ø1/16 in	3 Kgf	45 Kgf
15W	Ball Ø1/8 in	3 Kgf	15 Kgf
30W	Ball Ø1/8 in	3 Kgf	30 Kgf
45W	Ball Ø1/8 in	3 Kgf	45 Kgf
15X	Ball Ø1/4 in	3 Kgf	15 Kgf
30X	Ball Ø1/4 in	3 Kgf	30 Kgf
45X	Ball Ø1/4 in	3 Kgf	45 Kgf
15Y	Ball Ø1/2 in	3 Kgf	15 Kgf
30Y	Ball Ø1/2 in	3 Kgf	30 Kgf
45Y	Ball Ø1/2 in	3 Kgf	45 Kgf

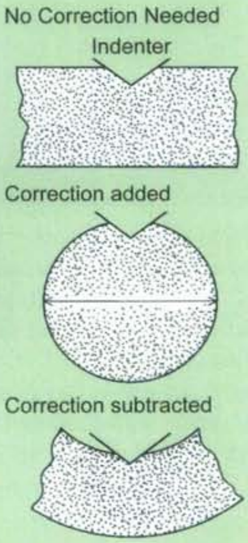
The most often used Rockwell hardness scale is the C scale. If a number happens to be 62 in C scale, it will be expressed as HRC62. The difference between each graduation in the HRC scale is the depth of 2 μm or 80 μin. In general, it can be said that the higher the number, the harder the metal. One of the shortcomings of the Rockwell system is that the numbers are generally limited to two digits and for higher hardness, the scale changes from C to A, for example, thus cutting off the linearity. Others such as Vickers are based on one continuous scale number.

Hardness Testing for Cylindrical Parts

It is absolutely necessary to have all three, *(a)* indenter, *(b)* cylindrical specimen, and *(c)* V-anvil, to form a single line.

To see if the indenter is truly on the apex of the cylinder, rotate the V-anvil 90° and check again.

A correction factor (see table below) must be added to the Rockwell hardness number for cylindrical surfaces.



Corrections added to Rockwell C, A , D values on convex cylindrical surfaces

Hardness number	Diameter of convex cylindrical test piece 1/4 6.4	3/8 10	1/2 13	5/8 16	3/4 19	7/8 22	1 25	1-1/4 32	1-1/2 in 38 mm
20	6.0	4.5	3.5	2.5	2.0	1.5	1.5	1.0	1.0
25	5.5	4.0	3.0	2.5	2.0	1.5	1.0	1.0	1.0
30	5.0	3.5	2.5	2.0	1.5	1.5	1.0	1.0	0.5
35	4.0	3.0	2.0	1.5	1.5	1.0	1.0	0.5	0.5
40	3.5	2.5	2.0	1.5	1.0	1.0	1.0	0.5	0.5
45	3.0	2.0	1.5	1.0	1.0	1.0	0.5	0.5	0.5
50	2.5	2.0	1.5	1.0	1.0	0.5	0.5	0.5	0.5
55	2.0	1.5	1.0	0.5	0.5	0.5	0.5	0.5	0
60	1.5	1.0	1.0	0.5	0.5	0.5	0.5	0	0
65	1.5	1.0	1.0	0.5	0.5	0.5	0.5	0	0
70	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0	0
75	1.0	0.5	0.5	0.5	0.5	0.5	0	0	0
80	0.5	0.5	0.5	0.5	0.5	0	0	0	0
85	0.5	0.5	0.5	0	0	0	0	0	0
90	0.5	0	0	0	0	0	0	0	0

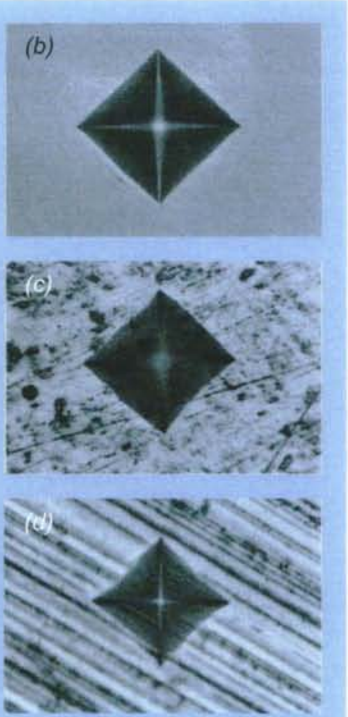
Corrections are approximate only, and represent the average to the nearest 0.5 Rockwell number, from numerous observations. The same number will be subtracted from concave cylindrical surfaces.

The chance of encountering convex cylinders such as shafts or pins is very high. Rockwell hardness is based on the assumption where the test specimen's surface is flat and smooth.

When the test piece is a small pin gauge, as in the above case, a correction factor must be added. In this case the number was found to be C-scale 60. To correct it, add 1 point because the diameter of this cylinder is approximately 1/2 inch. If the surface is concave, the value found in the table below should be subtracted instead of added.

Vickers and Knoop Testing Methods

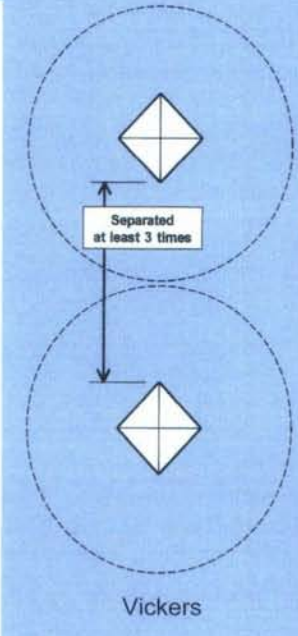
An indenter and microscope lenses in a Vickers hardness tester.

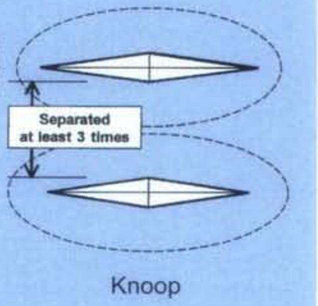


Indentations on various materials

The concept of modern hardness testing methods goes back to the year 1900 when Brinell established a method of indenting a test piece with a SØ10 mm steel ball under a load of up to 300 kg and calculated the surface area indented. Brinell measured the area indented in square millimetres.

Vickers, by contrast, represents the opposite end of the same principle. The indenter used is an inverted diamond pyramid as illustrated above *(b)* which produces an indentation so tiny that it must be checked by a microscope. Two diagonals of the indented pyramid will be measured and averaged; the area indented in μm will be the Vickers hardness number. The load can be as little as 1 gram. Between these two extremes Brinell and Vickers, lies the most popular of all hardness testers: Rockwell.





Only the longer length across will be measured in Knoop Hardness Numbers. It produces a much shallower indent, so that the diamond Indenter will not crack brittle materials such as ceramics.

Standard Reference Material (SRM) from NIST

National Institute of Standards & Technology
Certificate
Standard Reference Material® 2810
Rockwell C Scale Hardness - Low Range
Serial Number: 95N25094

Each SRM comes with a certificate verifying traceability to NIST

A close up showing the serial number and wooden case (underneath SRM)

In the US, there are several domestic manufacturers from which hardness standards can be purchased. When NIST studied the hardness numbers on the commercial grade standards, they discovered a significant variation in stated value among them. This was more than a decade ago, but this discovery prompted NIST to seriously look into hardness standards. SRM Hardness standard shown on this page is a direct result of their diligent and patient work during the last decade.

In their effort to pre-empt future variations in hardness numbers, NIST started to produce their own artefacts under the SRM program. As of this time, they are limited to three Rockwell standards in C-Scale and one ceramic standard.

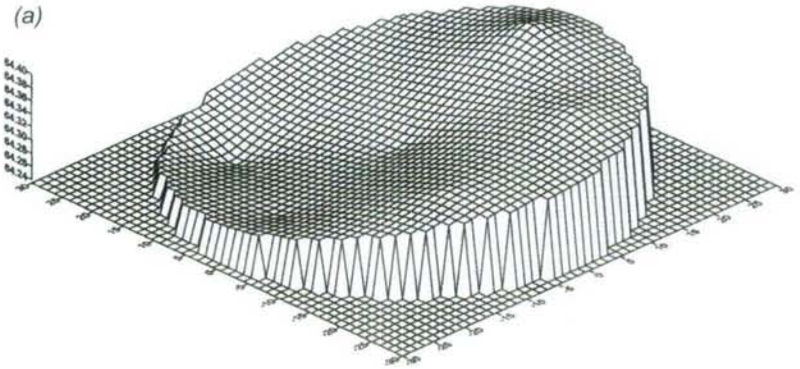
Rockwell Hardness Standards C-Scale

NIST SRM No.2810 (Low Range)	NIST SRM No. 2811 (Mid Range)	NIST SRM No. 2812 (High Range)
HRC 25	HRC 45	HRC 63

The hardness standards from NIST, under the SRM program are most certainly traceable to NIST and are the highest in the traceability tree. Their certificate *(a)* with explanation is extremely helpful in understanding the certification procedures at the NIST Metallurgy Department, led by Dr Samuel Low. Each standard is also supplied in a fitted wooden case *(b)*.

Under the SRM program, NIST offers more than 1,700 types of artefacts. The standards of surface roughness, particularly in the finer ranges, are also available. The SRM department may be reached at srminfo@nist.gov.

This wire frame chart *(a)* was provided by Dr. Low and Walter Liggett of the NIST Metallurgy Department. This is one of the NIST SRMs (Standard Reference Materials), with a very small amount of measurement uncertainty. Without a doubt, this is simply best hardness standard there is.



The National Research Council (NRC) in Ottawa, the Canadian counterpart of NIST, is recommending their industrial community to get in touch with NIST on the hardness standard issue. For this reason, this SRM standard works in both nations. The National Metrology Institute (NMI) in other nations need not reinvent the wheel, since the standard is readily available from the US. If so, the SRM hardness standard shown here will be the world-wide *de facto* standard for the Rockwell C-Scale.

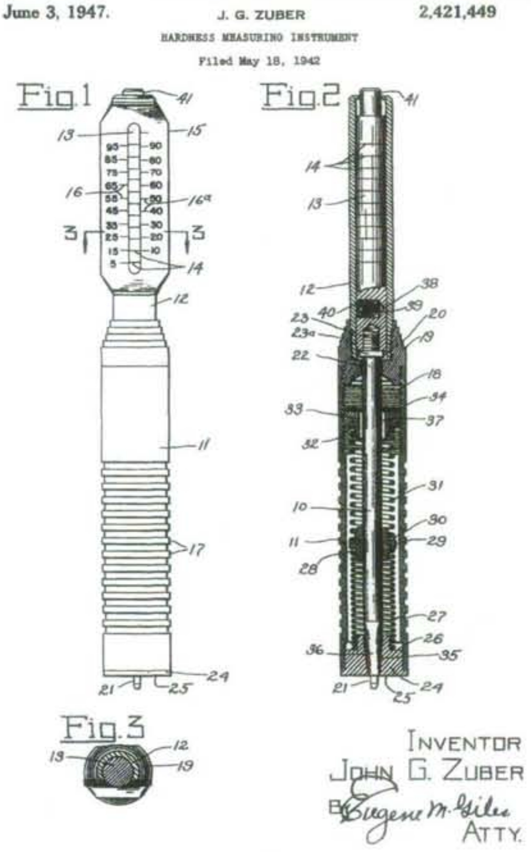
This specially designed calibration machine, featured with a HP interferometer to measure the depths of indents, was created for NIST in order to produce SRMs. In this picture, one such blank hardness standard is being indented for eventual certification by NIST.

Courtesy: NIST Metallurgy Dept.

The "Seat" (encircled) is the first indent and is not to be reported on the NIST certificate. It merely helps the calibration machine to make itself ready for the succeeding seven indents, each one of which is reported on the NIST certificate. Variations in the seven indents are small but cannot possibly be zero as the accompanied chart *(a)* above indicates. The blank hardness discs are supplied by Yamamoto of Japan and are subsequently indented at the NIST Metallurgy Department *(b)*.

The Durometer

A Durometer Test Block Kit. Each block is colour coded for easy identification. The indicated Durometer readings are derived from an average of 6 calibrated readings as per ASTM D-2240. For periodic verification of the calibration accuracy, take an average of 3 readings in different spots on each test block. The results should be ±2 Duro points.

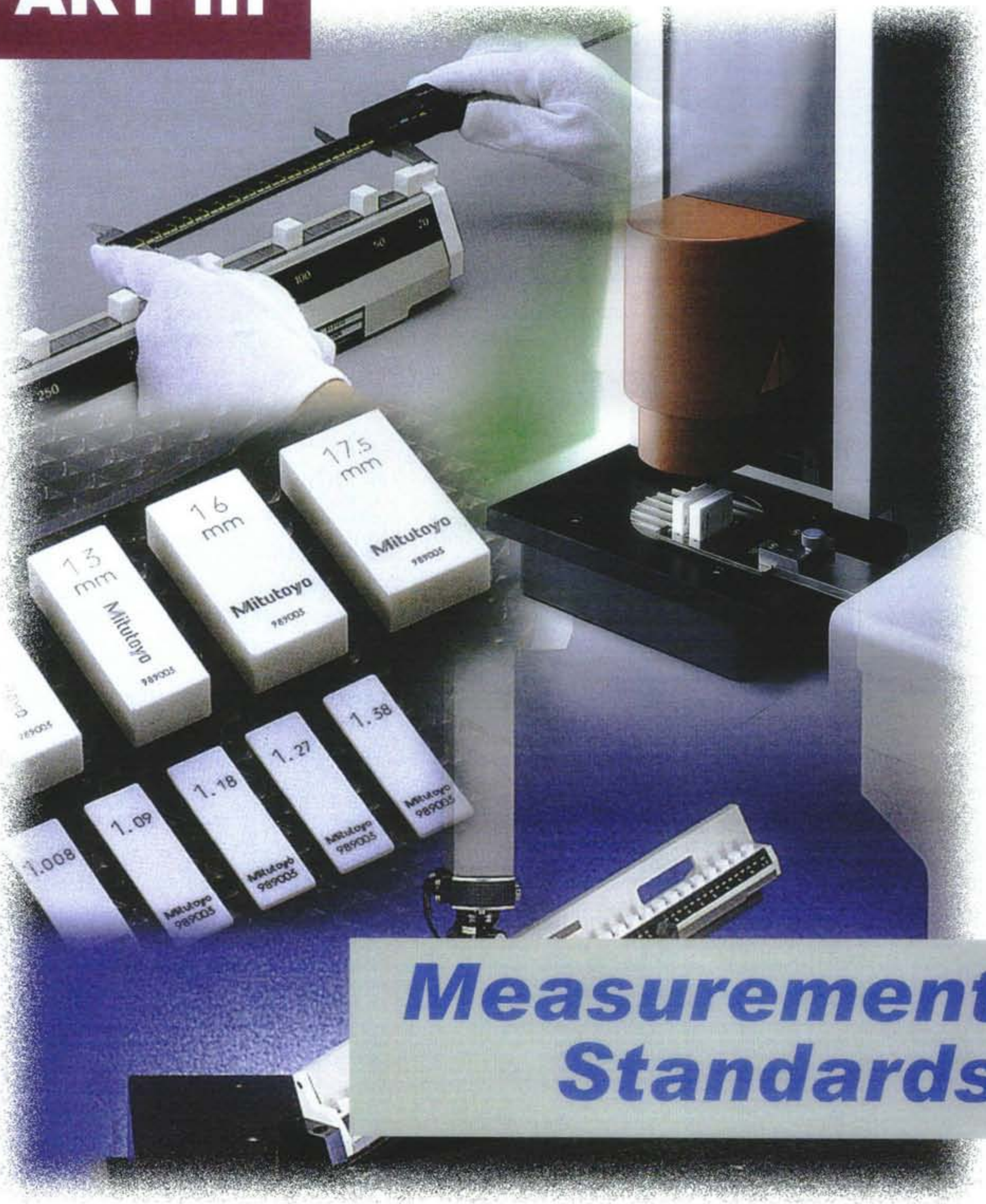


The objectives for this invention are numerous: (1) to provide a simple, accurate and reliable gauge for measuring hardness or compressibility of materials such as soft rubber, (2) to permit reading of the measurement even after removal of the gauge from the test material, but above all (3) to provide a pencil-size gauge with a test rod or what is called a "depressor" by which the hardness or compressibility is determined directly.

The embodiment of this patent at left, made of light aluminium is still sold by Rex Supply of Chicago. There are other Durometers in the market but the basic principle is no different. The intent is to quantify the compressibility of materials from 0 to 100. The original scale was a Vernier scale as shown here (at left), but dial and digital Durometers are also available. Graduations may be 10-90, or 20-90 and when they are featured with digital readout, the resolution can be 0.5 and the results can be uploaded to a computer for analysis. The standards are: ASTM D-2240, ISO 862 and ISO 7619.

The plunger (21) in the patent application is preloaded and extends .100 in from the face of the base (25). Each .001 inch is then one Durometer number, the hardest being 100. The construction is rather simple. The operator must try several locations to read the number.

PART III



Measurement Standards

PART III:
MEASUREMENT STANDARDS

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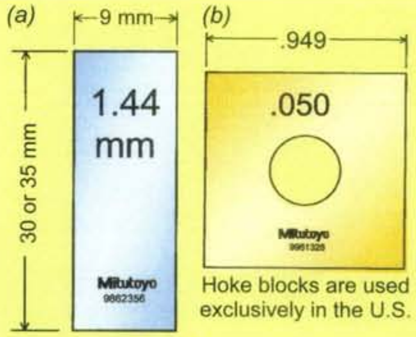
- Telescoping Gauge

Chapter 8 Gauge Blocks

"THE MOST PRECISE LENGTH"

Categorically speaking, there are two major types of standards: one is the end standard and the other is the line standard. The gauge blocks covered in this chapter are examples of end standards. Gauge blocks were originally conceived as production-type Go/No-Go Gauges before the turn of the 20th century. The inventor, Carl Edward Johansson, also developed numerous accessories which allowed gauge blocks to have a wider range of applications on the shop floor.

As will be seen on the following pages, Johansson was the inventor of what he called "combination" gauge blocks, that is, using several blocks that must be combined and wrung together to achieve various lengths. His gauge block was narrow, 9 mm in width, regardless of size. For this reason, Johansson's gauge blocks are called "Rectangular Blocks" *(a)* as opposed to the "Square Blocks" *(b)* invented by the American inventor William E. Hoke. Square blocks are also known as Hoke Blocks in the U.S. and they are used primarily by the automotive and aircraft industries there.



Rectangular blocks are 9mm in width

Hoke blocks are used exclusively in the U.S.

Square blocks *(b)* were designed in NBS much later than the Johansson blocks by the American inventor Hoke. Hoke's style featured a signature through hole in the middle regardless of its size, allowing him to develop tie rods for his gauge blocks.

The "Combination" Gauge Block Set

Fig. 1.

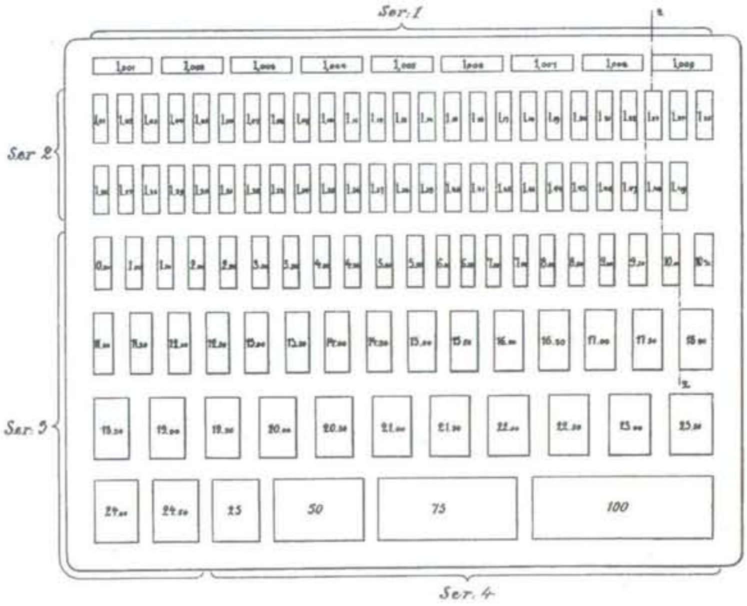


Fig. 2

Fig. 3

The original patent application submitted by C.E. Johansson, dated January 30^{th} 1904 in Sweden, included the figure at left. By this time the inventor of gauge blocks, Johansson, must have mastered the lapping techniques necessary to allow two lapped surfaces to "wring" tightly together. Though this was and still is a unique feature of gauge blocks, there was no word for "wringing" or "adhering" included in his application. Wringing, after all, is a natural phenomenon for which no one can claim exclusive ownership.

Johansson's patentable novelty was not the shape of gauge blocks, nor the method of steel making for which his country Sweden was famous for. His patent was granted on the basis of his select numerical order whereby the largest number of combinations can be achieved with the least number of gauge blocks. In his application, he came up with a set of 111 blocks. One of the significant parts of this patent was in the first horizontal series of nine, from 1.000 to 1.009 mm in steps of 1 μm (.000040 in). Those who followed his footsteps have neither added nor subtracted from his original design, with the notable exception of William Hoke who produced Square (or Hoke) blocks in the U.S. much later.

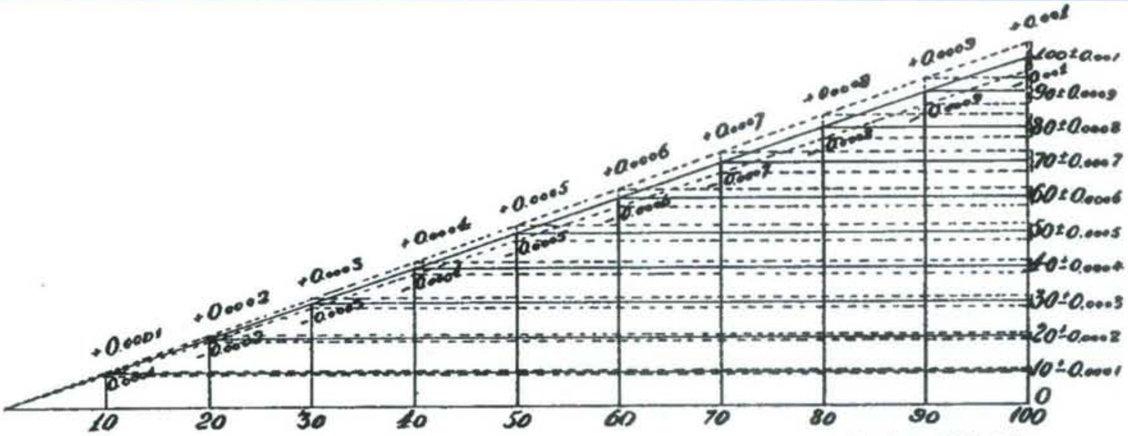
Courtesy: C.E. Johansson

The first gauge block set ever sold, consisting of 103 steel blocks, was purchased by the Stockholm Munitions Factory in 1899. This set shown here is now in the possession of AB C.E. Johansson in Sweden.

Gauge block sets of the same vintage produced by C.E. Johansson, very much like this example, are permanently displayed at the Smithsonian Institute in Washington, DC. His original set and modern gauge block sets are not very different. In fact, modern gauge block sets are identical to this set

Size and Tolerance Ratios

(a)



Courtesy: C.E. Johansson

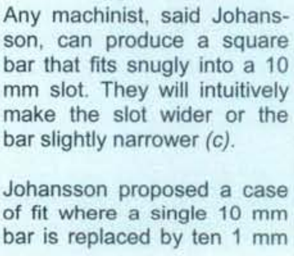
(b) Standard Tolerance Grade IT (ISO 286) Units in µm

Size (mm)	IT 1	IT 2	IT 3	IT 4	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11
80-120	2.5	4	6	10	15	22	35	54	87	140	220
50-80	2	3	5	8	13	19	30	46	74	120	190
30-50	1.5	2.5	4	7	11	16	25	39	62	100	160
18-30	1.5	2.5	4	6	9	13	21	33	52	84	130
10-18	1.2	2	3	5	8	11	18	27	43	70	110
6-10	1	1.5	2.5	4	6	9	15	22	36	58	90
3-6	1	1.5	2.5	4	5	8	12	18	30	48	75
0-3	0.8	1.2	2	3	4	6	10	14	25	40	60

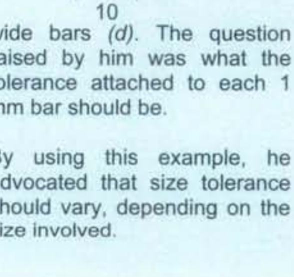
This is incomplete and partial. See ISO 286 for the complete table

During the period after the turn of the last century, C. E. Johansson was engaged in the production of firearms in Sweden. However, his interest was not limited to the numerical order or combination of gauge blocks and production of muskets alone. At the time, there was little understanding of the importance of tolerances: Longer barrels beyond the standard length were simply cut off. Johansson came up with a straightforward proposal to address that: larger sizes must take proportionally larger tolerances. In detail, his idea was to have a proportionally larger zone of tolerance for larger sizes, and in turn comparably smaller tolerances for smaller sizes. See table *(a)*. It was simple proposal, but nevertheless was the first step in the right direction: His principles indicated in the table *(a)* gave rise to the ISO 286 "System of Limits and Fits" *(b)*.

(c)



(d)

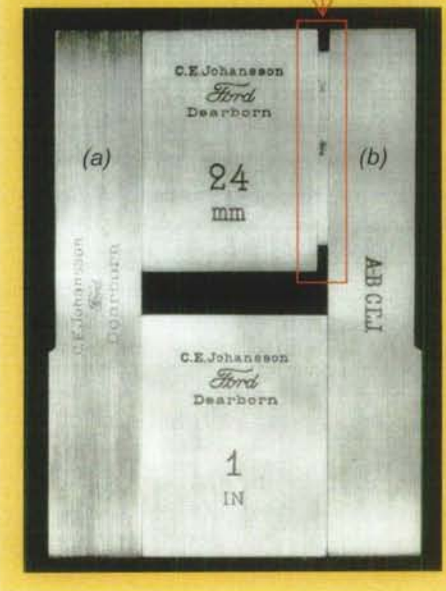


Any machinist, said Johansson, can produce a square bar that fits snugly into a 10 mm slot. They will intuitively make the slot wider or the bar slightly narrower *(c)*.

Johansson proposed a case of fit where a single 10 mm bar is replaced by ten 1 mm wide bars *(d)*. The question raised by him was what the tolerance attached to each 1 mm bar should be.

By using this example, he advocated that size tolerance should vary, depending on the size involved.

Inch to Metric Conversions



1 inch = 25.4 mm (exact)

As a young man C.E. Johansson resided in Minnesota for two years. He then went back to his native land Sweden and subsequently earned the reputation as "the world's most accurate man".

When he returned to America after thirty five years, Henry Ford and Johansson worked together to produce these gauge blocks. The blocks at right were made in Dearborn, MI. Ford's emblem is engraved for this reason.

Two bars *(a)* and *(b)* are accessories wrung together with gauge blocks. To be able to wring as shown here, 25.4 mm (24 + 1.4) and 1 inch must be equal. If not, wringing will not be achieved. This is another practical way to prove that 1 inch equals 25.4 mm exactly.

To produce accurate gauge blocks, base materials must be readily available. Johansson's country, Sweden, is known for its excellent steel.

Year	Length of 1 in Gauge Block
1947	25.399931 mm
1932	25.399950 mm
1922	25.399956 mm
1895	25.399978 mm

Source: NIST (NIST Monograph 180)

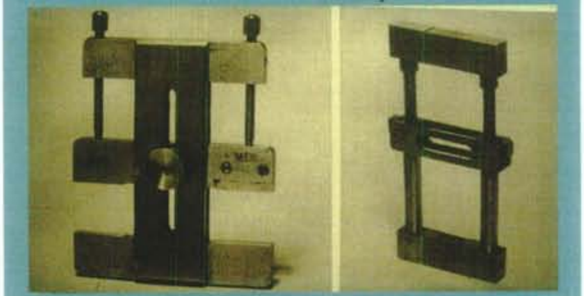
In the mid 1800s, there were two major units of length — inch and metric. The artefact standards, such as the metre bar at NIST, were known to be slightly unstable. The table at left indicates a trend of a one inch gauge block getting smaller over time.

In 1866, the U.S. Surveyor General decided to base all geodetic measurements on an inch defined by the international metre. In the meanwhile across the Atlantic, England continued to use the yard bar to define the inch. The two different inches in the UK and US continued to coexist for nearly 100 years until quality control issues during the World War II showed that the variation between them was large enough to pose problems in interchangeability.

The "combination gauge blocks" — so named by Johansson — were originally created to perform Go/No-Go judgments at his plant where muskets were made and assembled. At the time, product tolerances were loose, and this method worked well. What was outstanding was the fact that his combination gauge blocks were so accurate that the combined blocks, properly wrung together, represented the most accurate dimensions even by today's standards.

Johansson's Go/No-Go Gauges

Courtesy: C.E. Johansson



Adjustable limit gauge for outside measurements where MAX and MIN are engraved.

Adjustable gauge for inside dimensions.

In both cases, the operator will use these Go/No-Go gauges to make sure that the feature is within the stated limits.

Rectangular or Square?

Johansson's Rectangular Gauge Blocks

Johansson's rectangular-style gauge blocks shown below are known as the Rectangular type. They are universally used and specified in the ISO standard. Johansson set the thickness of his gauge blocks at 9 mm. Because of this precedence, modern gauge blocks are also 9 mm in thickness. William Hoke, the American inventor who worked at NBS, thought that he could improve upon Johansson's design. Long rectangular gauge blocks shown below are featured with holes for connecting clamps. Johansson's original gauge block sets were up to 100 mm; anything longer than that is called "long block". The longest standard single-piece block is 500 mm or 20 inches.

Longer than 500 mm or special gauge block sizes are made by skilled technicians.

Johansson selected 20°C when he calibrated his gauge blocks, despite the fact that the prevailing standard temperature was 0°C. He deviated from the standard because from experience he knew that no one in the shop was measuring at 0°C, and that the machine shop temperature in Europe at the turn of the 20th century was 20°C on average. Being a man of pragmatic ideas, Johansson measured all of his gauge blocks at 20°C. Many of his gauge blocks became the artefact standards of the U.S. His choice of temperature was later acknowledged by ISO1-1975, which is a rare ISO standard consisting of only one page and one line.

Without a doubt, precision as we know it today started with Johansson, who paved the way for others to follow.

Square or "Hoke" Gauge Blocks

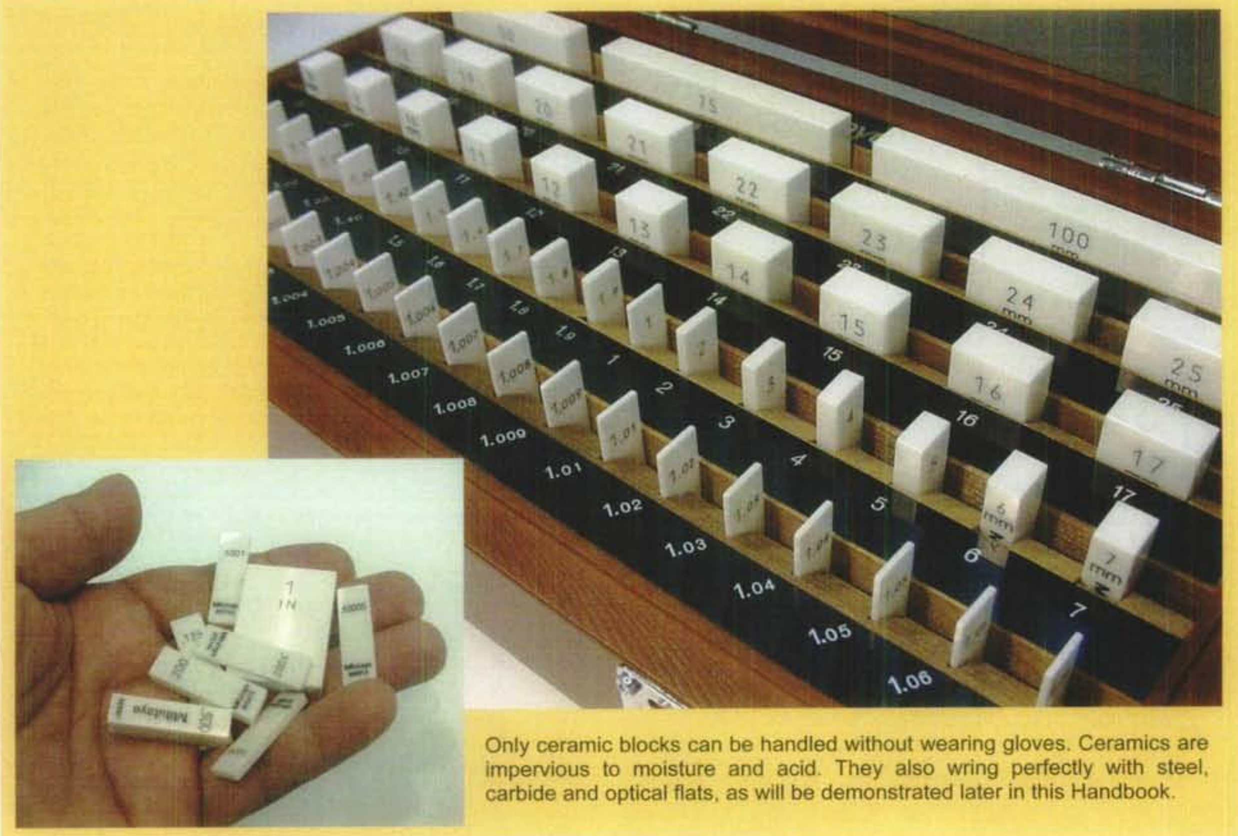
In 1917, the American inventor William Hoke proposed an improvement upon Johansson's original gauge block design to the National Bureau of Standards (NBS). Funds were obtained from the U.S. Ordnance Department for the project and 50 sets of 81-piece gauge blocks were produced. They were then disc-shaped and one inch in diameter with a signature through-hole in the middle (see photo at bottom). Later, the round block turned into 1 x 1 inch square as shown below. While Johansson's gauge block was only 9 mm thick and fragile when it stood upright, Hoke's block was massive enough and less likely to be tipped over accidentally on the granite surface plate.

Because they are designed and made in the U.S., the "Hoke" type gauge blocks are used exclusively in North America in the automotive and aircraft industries. Both inventors, Johansson and Hoke, developed accessories for their gauge blocks to facilitate a broader range of applications on the production floor. Adjustable tie rods designed for Hoke blocks work well in holding Hoke blocks in one piece. They nevertheless must be wrung first before the tie rod is inserted. The tie rod is to hold the blocks together without clamping them.

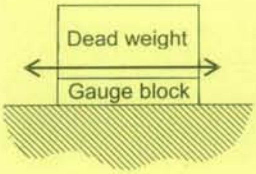
Courtesy: NIST

The Original Hoke Block. Despite its name, the original "square" block was round. Hoke added the through hole to overcome domed top and bottom ends

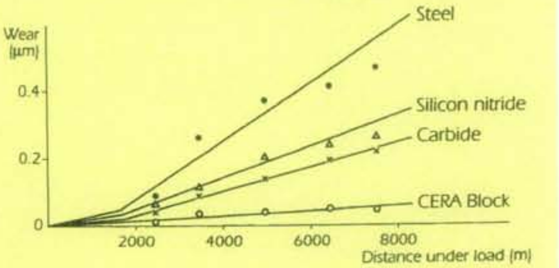
Ceramic Gauge Blocks



Only ceramic blocks can be handled without wearing gloves. Ceramics are impervious to moisture and acid. They also wring perfectly with steel, carbide and optical flats, as will be demonstrated later in this Handbook.



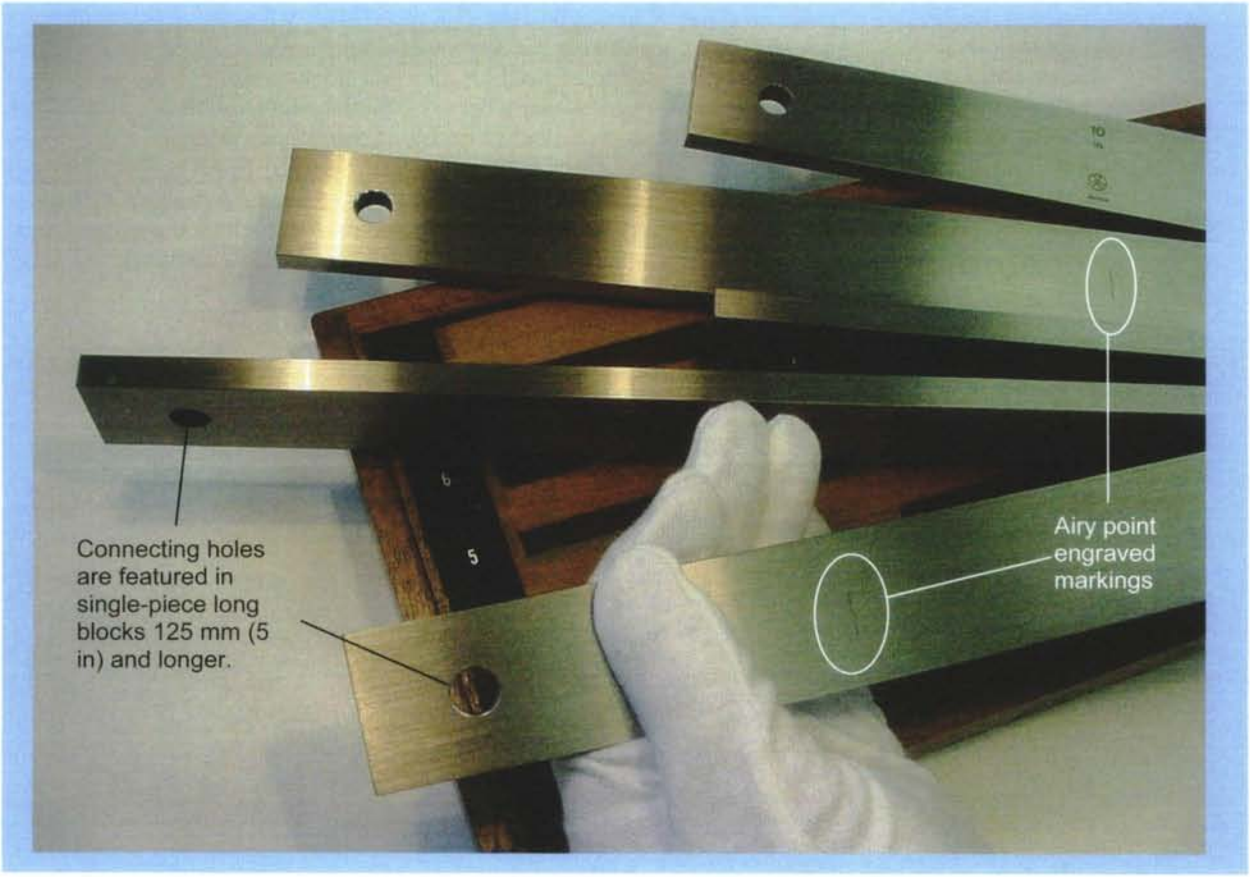
The wear factor of the Cera blocks was tested against two steel plates: FCD45 and SUJ-2. Cera blocks displayed the least amount of wear when compared with other materials.



C.E. Johansson achieved an accuracy of 1 micrometre (0.001 mm), an amazing feat for his time. His steel gauge blocks were renowned for possessing precise length, and he earned the reputation as the "most precise man". Scientists since then have been searching for more wear resistant materials, introducing Chrome-carbide followed by Zirconium (ZrO_2) ceramic material gauge blocks. Ceramics are the latest addition, going back only a decade or two.

During the 1970s, ceramic emerged as a new substrate for the chip-making industry. The technology to produce ceramics for the chip-making industry soon migrated into the field of metrology. Gauge blocks shown here are prime examples: They are 10 times more wear resistant than conventional steel blocks, and remain stable for many years. If left untouched, ceramic blocks will lose approximately 25 nanometres (.000001 in) in about 10 years. The thinnest 1 mm ceramic block can resist the force exerted by a human hand. They also wring perfectly against optical flats, steel and carbide blocks, as long as the mating planes remain flat and equal in surface finish.

Rectangular Long Blocks



The longest single-piece block included in a standard set is 100 mm (4 in), and longer than that are known as "long blocks". Carl E. Johansson started with 1 mm and ended with 100 mm in his original gauge block set. Longer ones were added later. See table *(a)* and *(b)* at right. Note: these longer single-piece gauge blocks are much easier to handle in real life than two or more gauge blocks wrung together, no matter how perfect the wringing method may be.

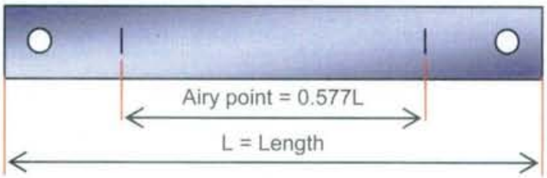
(a)

Metric Long Blocks (single-piece)			
125 mm	150 mm	175 mm	200 mm
250 mm	300 mm	400 mm	500 mm
600 mm	700 mm	750 mm	800 mm
900 mm	1000 mm		

(b)

Inch Long Blocks (single-piece)			
5 in	6 in	7 in	8 in
10 in	12 in	16 in	20 in

Longer single-piece and special blocks are also available



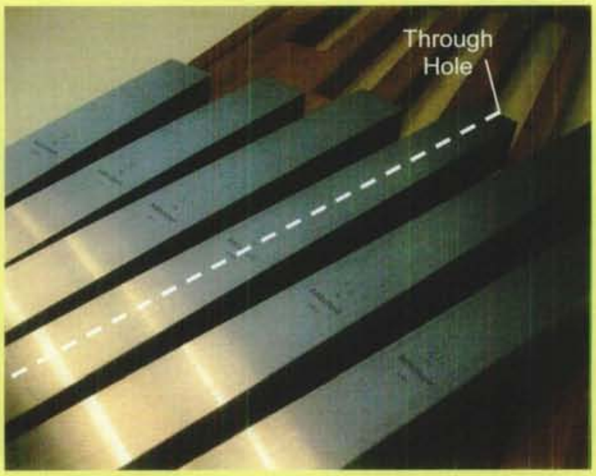
When long blocks are placed horizontally, they must be supported at the Airy points. These points allow both ends of the gauge block to stay parallel to each other.

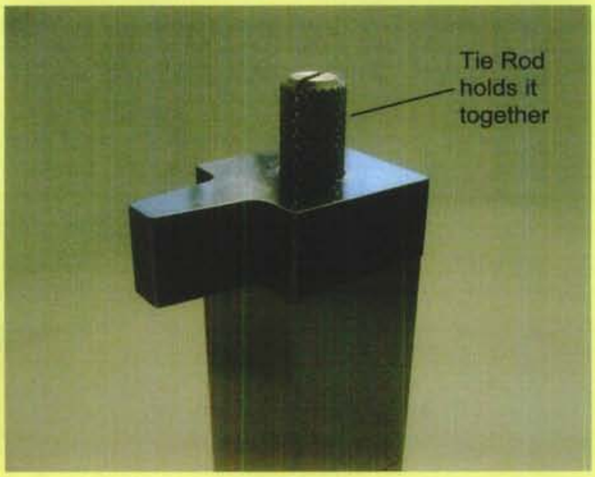
Gauge Block Accessories

Both Johansson, the original inventor of gauge blocks, and later Hoke, who attempted to improve upon the Johansson design, worked on a series of accessories after they completed their designs. Gauge blocks with accessories are intended to be used on the shop floor for Go/No-Go application. Unlike ring gauges which cannot be grow larger or smaller once produced, the merit of gauge blocks is in the ability to easily compose any number of blocks together to achieve any length.

When Johansson invented gauge blocks, his mathematical theory was to use a minimum number of blocks for a maximum number of combinations. It is therefore understandable that the gauge blocks were originally developed as production gauges. To facilitate this use, accessories such as the set shown below were created to facilitate applications on the production floor.

In almost all cases, standard gauge block sizes start with 1 mm or .050 in, rectangular or square type. Unique to the square gauge blocks is the signature hole in the middle.





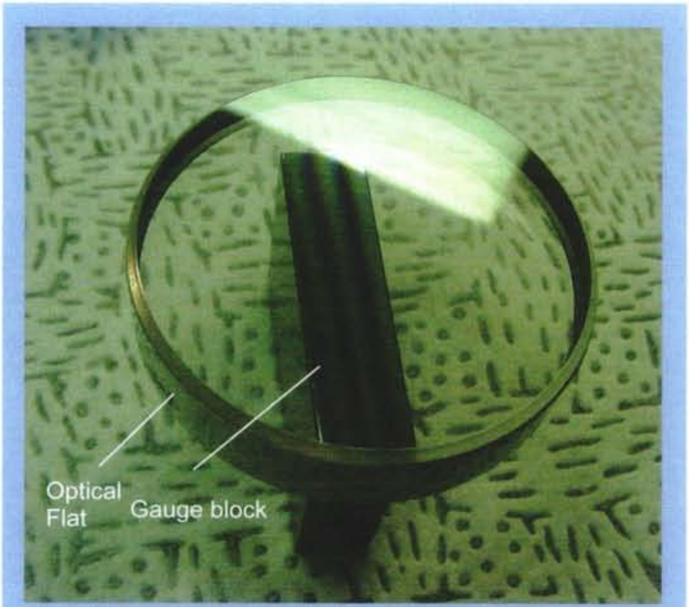
These holes are for connecting rods to pass through; holding the combination together after wringing is completed. These accessories greatly enhance the merits of square gauge blocks.

Optical Flats

Optical Flats are known to be the most flat objects ever made. Their sizes can be as large as 150 mm (6 in) in diameter for shop application or even much larger for other purposes and offer flatness within 25 nanometres (.000001 in) or much less depending upon the grade.

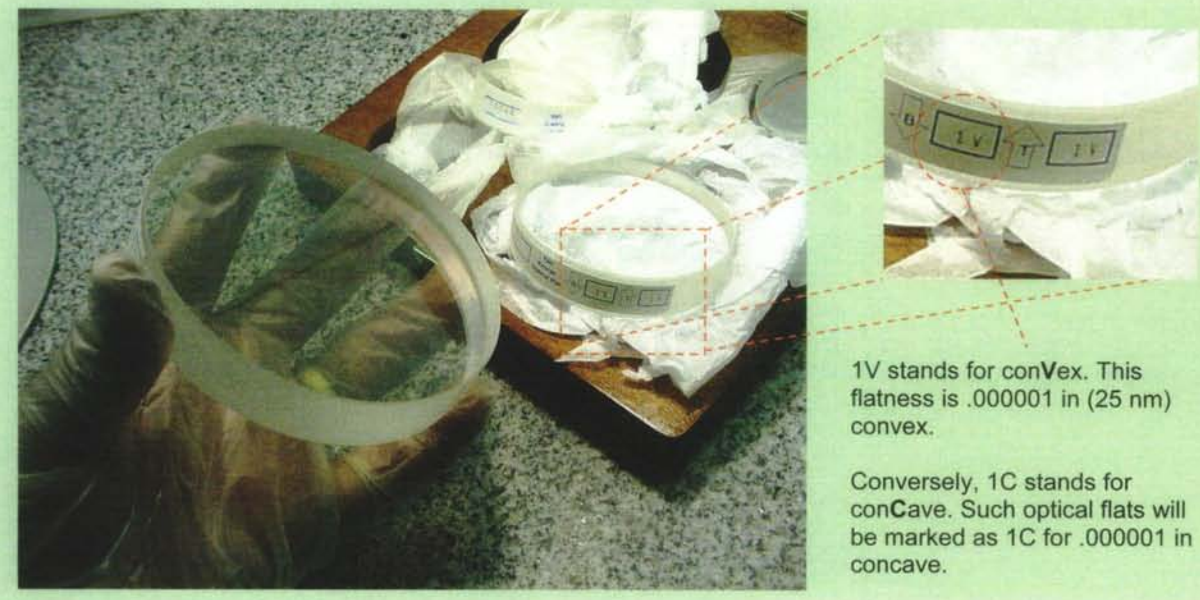
Optical flats used in the calibration lab to check out-of-flatness condition of gauge blocks as shown here. Double-sided and small-diameter optical flats are used to check parallelism between measuring faces of a micrometer (see page 145).

So long as the surface in question is relatively flat and finely ground or lapped and reflective, the light passing through the optical flat placed on top of it will bounce back. A fringe pattern will appear as shown in *(a)*. This is a quick way to see the flatness of the entire surface. Under green or pink monochromatic light, the dark bands are roughly 250 nm (.000010 in) apart.



The dark bands are the fringes, and are so straight that the surface appears to have a flatness of 50 nanometres or less.

Optical flats resting on a surface with a small wedge of air in-between can be rotated 90° to see the flatness across the surface. Curved dark patterns indicate the lack of flatness and the degree of out-of-flatness can be calculated by interpreting the line. Optical flats which are flat on one side only can indicate flatness, and when they are double-faced they can check the parallelism between opposing faces.



1V stands for con**V**ex. This flatness is .000001 in (25 nm) convex.

Conversely, 1C stands for con**C**ave. Such optical flats will be marked as 1C for .000001 in concave.

How to Select Block Combinations

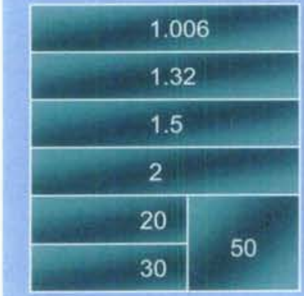
Say you have a dimension, 55.826 mm, which you want to create using gauge blocks.

No → **55.826** ← Yes

How to select?

Do not pick the big blocks first. This way makes it harder to select which blocks to use and you might run out of possible combinations as the number of small blocks left grows smaller.

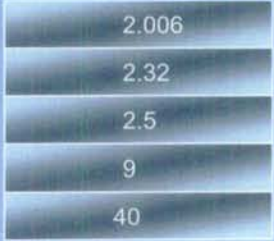
(a)

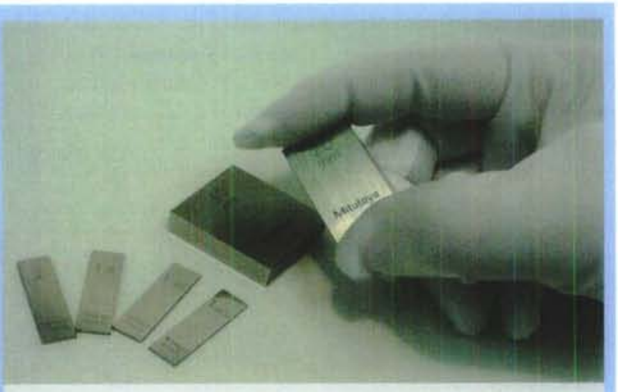


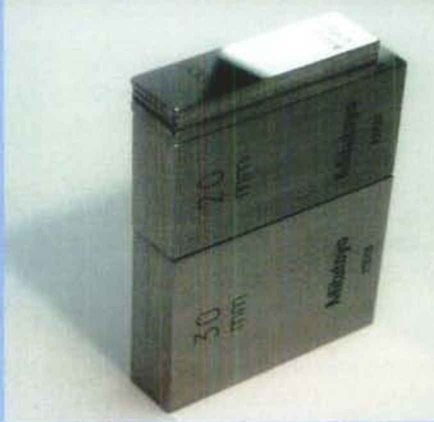
Pick the smallest number first and work from right to left. The last number in this case is 1.006 mm. It can also be 2.006 mm (see next page). Taking the last number first makes it easier to select which blocks to use.

(b)

(Based on 2 mm steps)





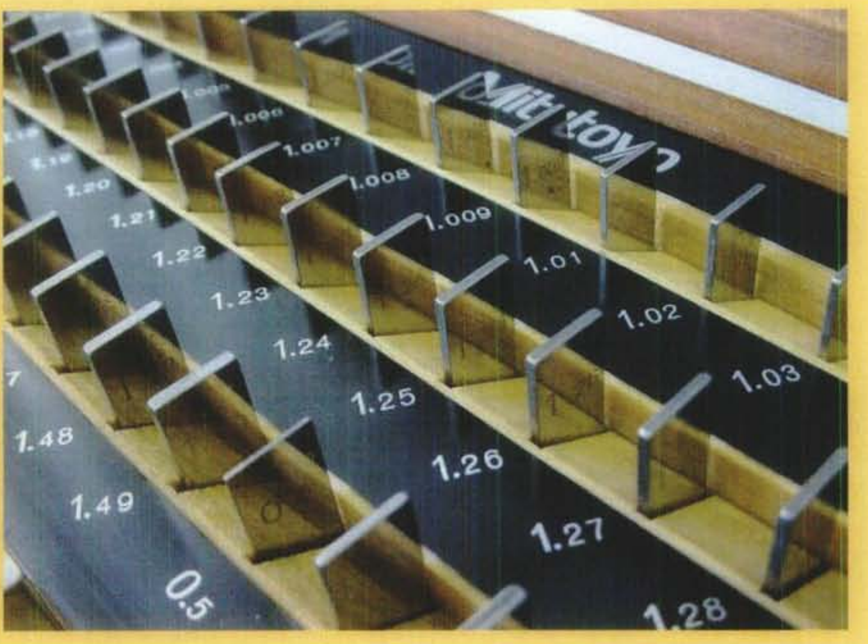


1.006
1.32
1.5
2
20
30
―――
55.826

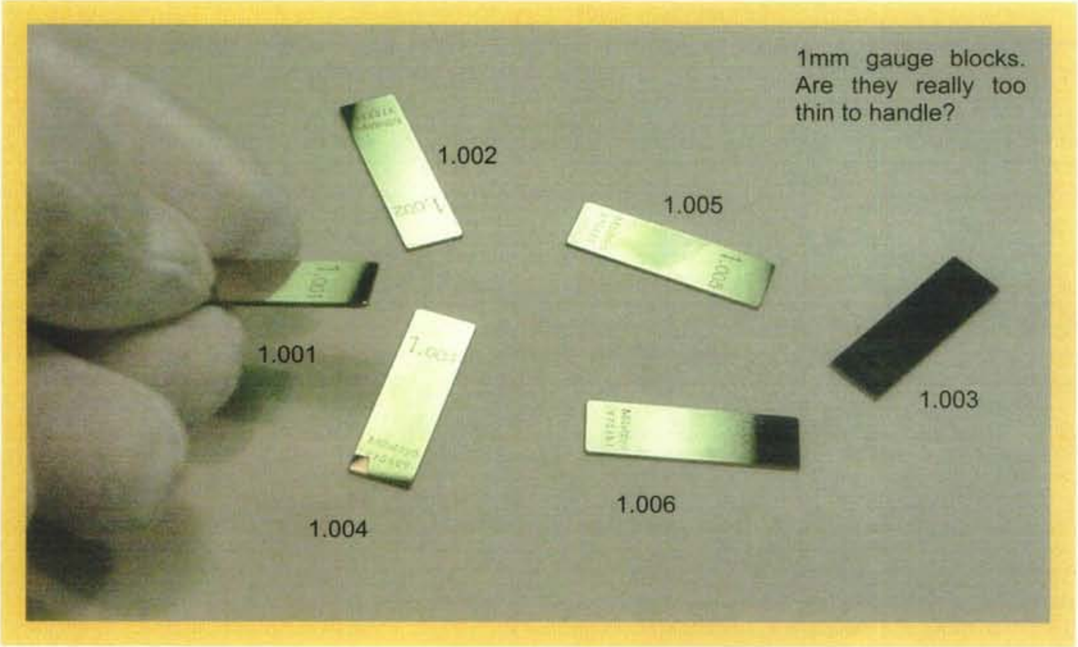
This set is a standard 87-piece metric set, of which 60 pieces are over 1 mm but less than 2 mm. This set is the traditional 1 mm based metric set.

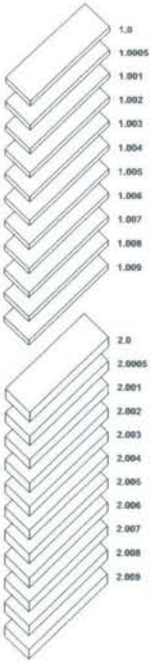
The set includes every 0.5 mm and 10 mm interval up to 100 mm, which is the largest block.

Some technicians feel 1 mm based blocks such as this is too thin to handle. For them, 2 mm-based metric blocks are also available (see next page).



2mm-based Metric Gauge Blocks


1mm gauge blocks. Are they really too thin to handle?



It has long been the standard of the industry to have 1 mm gauge blocks first and start to build up dimensions *(a)*. This practice originated from none other than the inventor, C. E. Johansson.

When metric started to come into the States in earnest, QC managers who used to handle .100 in (2.54 mm) based blocks found 1 mm-base blocks too flimsy and hard to work with. The solution was to produce 2 mm-base gauge blocks for those who handle both inch and metric blocks. Compare the 2 example gauge block combinations in the previous section. Clearly whether 1 mm or 2 mm is used is only a matter of personal preference.

So, to make a long story short, 2 mm based blocks *(b)* were added onto the already complete metric selection *(a)*. If dimensions on the blueprints are more than 2 mm, it will be a good idea to select this series. Sizes smaller than 2 mm, 5 µm for instance, can be made by having two gauge blocks: 2.005 mm and 2.0 mm side by side, and taking the difference between the two blocks.

Individual Metric Gage Block Sizes (Unit in mm)					
0.20	1.06	1.43	2.12	2.49	18.0
0.25	1.07	1.44	2.13		18.5
0.30	1.08	1.45	2.14	2.5	19.0
0.40	1.09	1.46	2.15	2.6	19.5
0.405	1.10	1.47	2.16	2.7	20.0
0.41	1.11	1.48	2.17	2.8	20.5
0.42	1.12	1.49	2.18	2.9	21.0
0.43	1.13		2.19		21.5
0.44	1.14	1.5	2.20	3.0	22.0
0.45	1.15	1.6	2.21	3.5	22.5
0.46	1.16	1.7	2.22	4.0	23.0
0.47	1.17	1.8	2.23	4.5	23.5
0.48	1.18	1.9	2.24	5.0	24.0
0.49	1.19	*(b)*	2.25	5.5	24.5
0.50	1.20	**2.0**	2.26	6.0	25.0
0.60	1.21	**2.0005**	2.27	6.5	
0.70	1.22	**2.001**	2.28	7.0	30.0
0.80	1.23	**2.002**	2.29	7.5	40.0
0.90	1.24	**2.003**	2.30	8.0	50.0
(a)	1.25	**2.004**	2.31	8.5	60.0
1.0	1.26	**2.005**	2.32	9.0	70.0
1.0005	1.27	**2.006**	2.33	9.5	80.0
1.001	1.28	**2.007**	2.34	10.0	90.0
1.002	1.29	**2.008**	2.35	10.5	100.0
1.003	1.30	**2.009**	2.36	11.0	125.0
1.004	1.31		2.37	11.5	150.0
1.005	1.32	2.01	2.38	12.0	175.0
1.006	1.33	2.02	2.39	12.5	200.0
1.007	1.34	2.03	2.40	13.0	300.0
1.008	1.35	2.04	2.41	14.0	400.0
1.009	1.36	2.05	2.42	14.5	500.0
	1.37	2.06	2.43	15.0	
1.01	1.38	2.07	2.44	15.5	
1.02	1.39	2.08	2.45	16.0	
1.03	1.40	2.09	2.46	16.5	
1.04	1.41	2.10	2.47	17.0	
1.05	1.42	2.11	2.48	17.5	

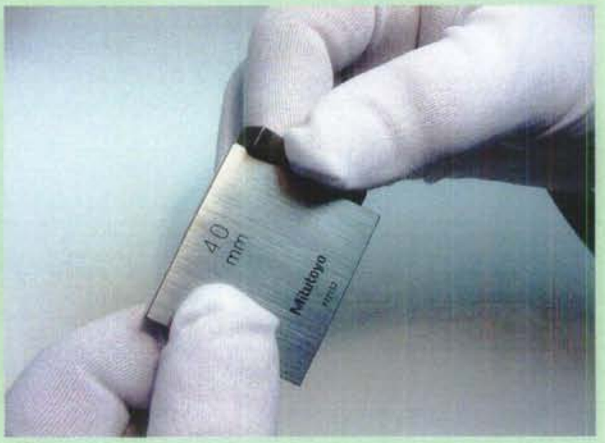
How to Wring Gauge Blocks

Wringing is a puzzling phenomenon. It is understood that a thin film of oil, in the order of a few nanometres, makes both faces cling together. If left untouched, blocks wrung tightly increase tightness and eventually become so tight that it is difficult to separate them by hand.

It is important that the wringing is done properly. Loosely wrung gauge blocks cannot accurately represent dimensions (it will always be larger). Presented here is a basic method of wringing for beginners, and a more advanced strategy for wringing different types of gauge blocks is presented on the next page.

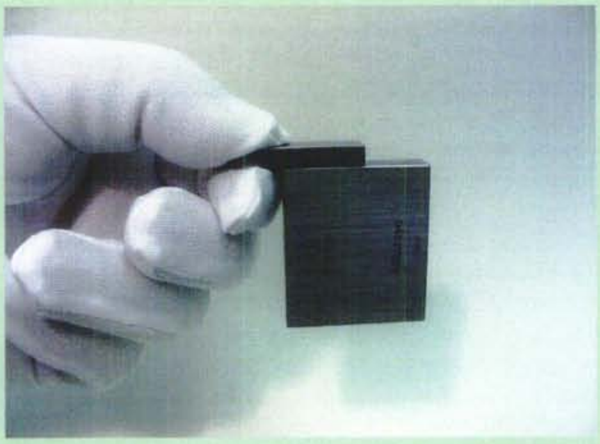
Basic Steps to Wring Gauge Blocks Together:

Step 1:
Put two blocks together perpendicularly and push them together. Now slide them until a strong force is felt, like a fish caught on a line, pulling it down.



Step 2:
Turn the top block slowly until the pair is parallel, making sure force is applied constantly.

Step 3:
The completed combination. This pair will need to be tested to determine how well they are wrung.



Step 4:
To make sure they are tightly wrung, hold one by the edge and lift the other. Make sure they do not crumble and remain tight.

Reasons for poor wringing:

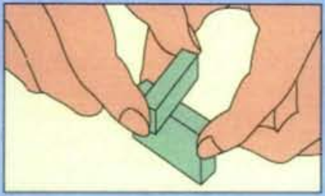
1. Gauge block is dirty
2. Surface is damaged or scratched
3. Too much oil on surface
4. Not enough pressure during wringing process
5. Must slide gingerly until it starts to grab.

If not, be patient and try again.

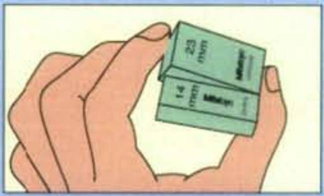
Tip: Don't try to wring large gauge blocks together immediately. Instead, start with smaller blocks: The thinner the block the easier the wringing will be. Start with this and gradually learn how to wring two large ones together, as shown below. It is just a matter of practice and patience.

Advanced Steps to Wring Gauge Blocks Together:

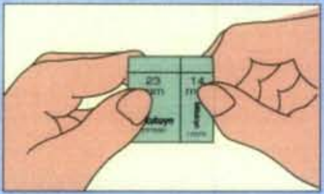
Wringing two thick gauge blocks:



Bring the two measuring faces into contact with each other at right angles.

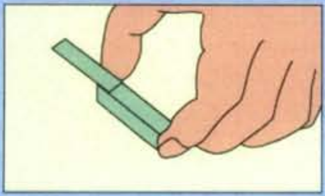


While applying a small amount of pressure, gently turn one gauge block on the other. You will feel the two blocks stick together.

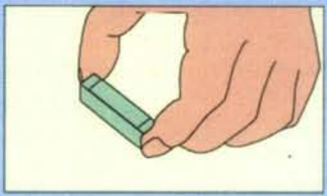


Slide one gauge block over the other so that the sides of the gauge blocks are flush with each other.

Wringing a thin gauge block to a thick gauge block:

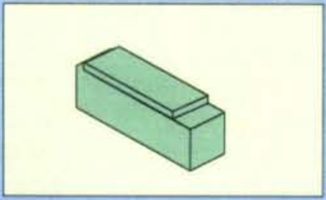


Place one end of the thin gauge block onto one end of the thick gauge block.

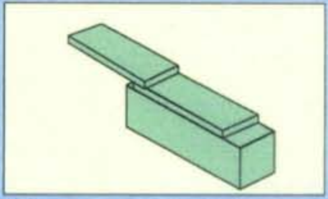


While applying pressure evenly over the entire wringing surface, slide the thin gauge block over the other until the two measuring faces coincide with each other.

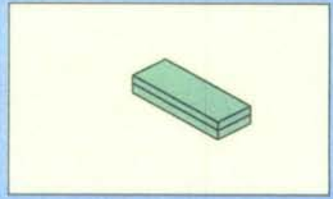
Wringing two thin gauge blocks:



To prevent the gauge blocks from bending, temporarily wring one of the thin gauge blocks to a thick gauge block that will be used as a support.



Wring the other thin gauge block to the first block.



Remove the thick gauge block.

Strategies in Wringing Gauge Blocks

Step 1: Decide on the combination of gauge blocks to be used while keeping the following points in mind:

a. Use as few gauge blocks as possible to obtain the required dimension.

b. Select thick gauge blocks whenever possible.

c. Select gauge blocks starting with the one that has least significant digit required, and then work up to ones with more significant digits.

Step 2: Clean the gauge blocks with an appropriate cleaning agent (see page 105 for cleaning method).

Step 3: Check the gauge blocks for burrs. Use an optical flat to check for burrs, as follows:

a. Clean the measuring face.

b. Gently bring the optical flat into contact with the measuring face.

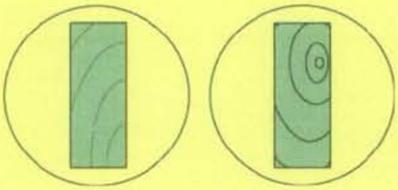
c. Gently slide the optical flat on the measuring face and interference fringes will appear.

Check 1: *If no interference fringes can be seen, a large burr or dust may be contaminating the measuring face.*

d. Gently press the optical flat against the measuring face and the interference fringes will disappear.

Check 2: *If the interference fringes disappear, it indicates that there is no burr present.*

Check 3: *If the interference fringes remain partially, gently move the optical flat to and fro. If the fringes are seen in the same location on the measuring face, there is a burr on the gauge block surface; if the fringes remain in the same location on the optical flat, there is a burr on the optical flat.*



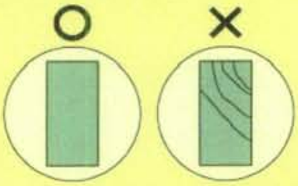
Step 3 (cont'd):

e. Remove burrs, if any, from the measuring face using an Arkansas stone (see page 104 for types of damage).

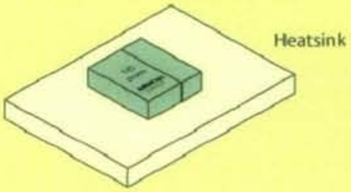
Step 4: Apply very small amount of oil to the measuring face. Spread it evenly over the entire surface, then wipe it clean. Grease, spindle oil, or Vaseline is normally applied.

Step 5: Gently bring the two measuring faces into contact using one of the methods introduced on the previous page, depending on the sizes of the gauge blocks to be wrung together.

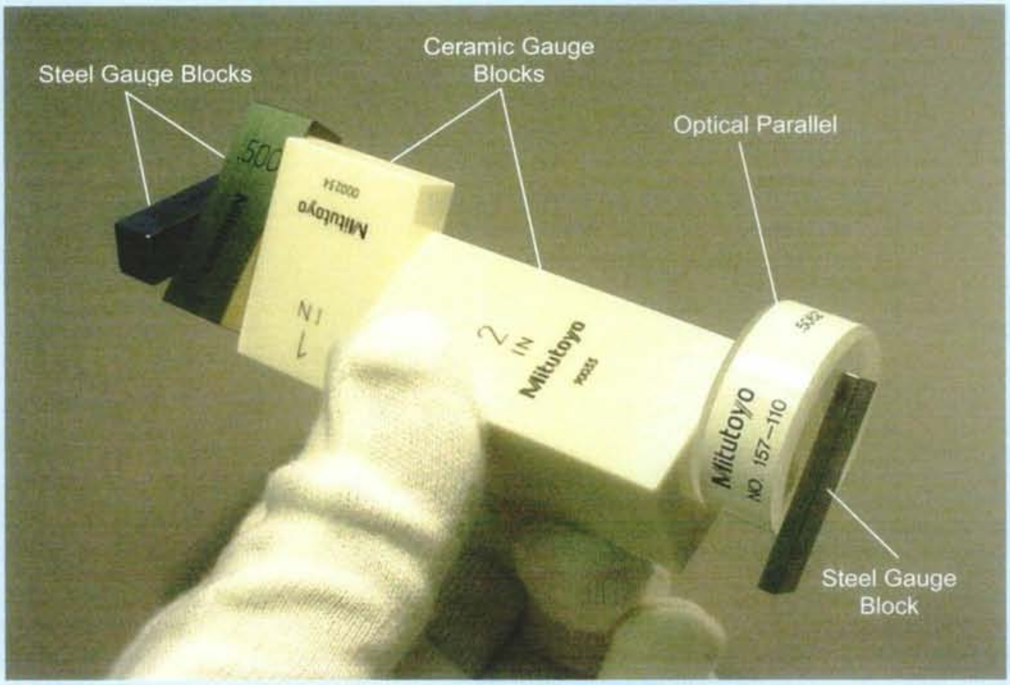
Step 6: Check the wringing condition with an optical flat. If there are irregular interference fringes, wringing has not been completed successfully.



Step 7: Wipe the measuring faces clean and thermally stabilise the gauge blocks on a heatsink before measurement (if necessary).



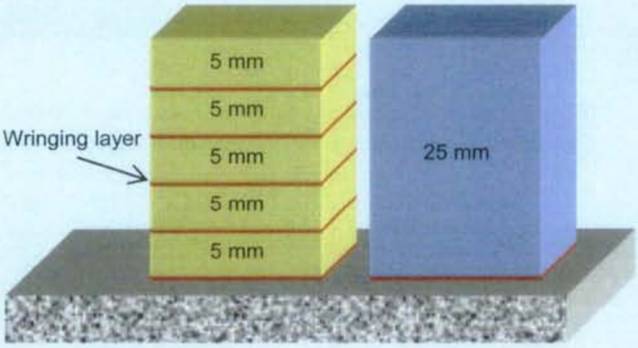
Wringing Layers



Different materials can be wrung together so long as their surface finish and flatness are high enough

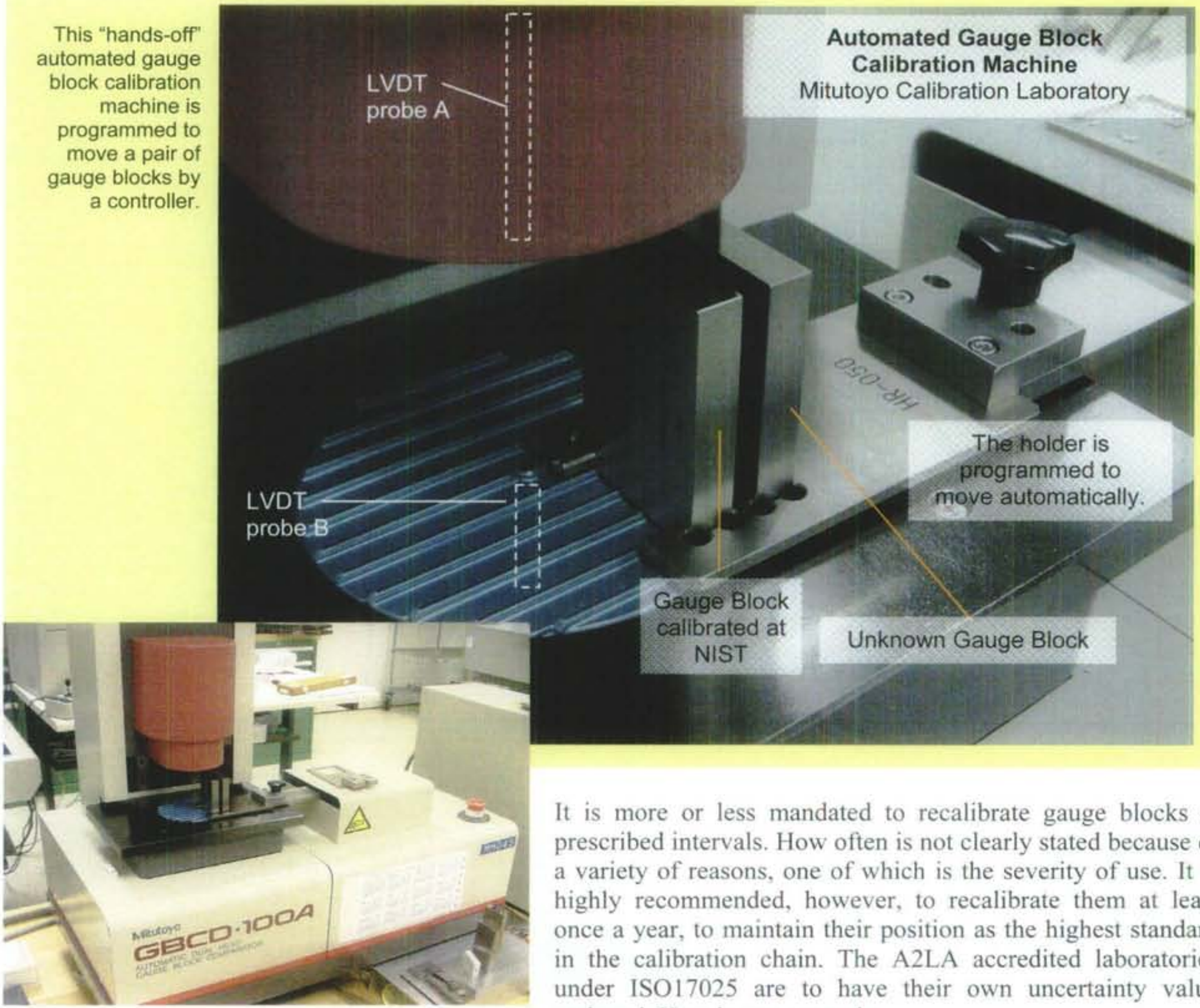
5 operators were asked to each wring five 5 mm gauge blocks to produce a 25 mm combination. The purpose of this test was to measure the actual thickness of wringing layers by comparing against a single 25 mm block. In conclusion, if blocks are wrung properly, the wringing layer may be almost disregarded because of its thickness: generally 25 nm or .000001 in.

Novice Operator E added 0.04 μm (1.6 μin) to the five block combination. He finished last in this test. In contrast, expert operator C wrung five 5 mm blocks together and made them "shorter" than 25 mm. This phenomenon is not uncommon. In short the wringing layers, as shown in the above table, are so thin that it can be almost disregarded for most applications. Operator B and C are experts, as is Operator A. One way to find out whether the blocks are well wrung is to try to pull them apart. If a stack of gauge blocks stays tight, the wringing is successful.



Operator	Name (ID)	Single layer of wringing film	Total buildup 5 x 5 mm blocks	
Expert	A	+ 0.0025 μm	+ 0.01 μm	(+0.4 μin)
	B	0	0	(0)
	C	- 0.0025 μm	- 0.01 μm	(-0.4 μin)
Novice	D	+ 0.005 μm	+ 0.02 μm	(+0.8 μin)
	E	+ 0.01 μm	+ 0.4 μm	(+1.6 μin)

Recalibration Cycle



Automated Gauge Block Calibration Machine
Mitutoyo Calibration Laboratory

This "hands-off" automated gauge block calibration machine is programmed to move a pair of gauge blocks by a controller.

The holder is programmed to move automatically.

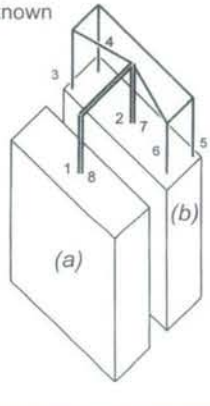
It is more or less mandated to recalibrate gauge blocks at prescribed intervals. How often is not clearly stated because of a variety of reasons, one of which is the severity of use. It is highly recommended, however, to recalibrate them at least once a year, to maintain their position as the highest standard in the calibration chain. The A2LA accredited laboratories under ISO17025 are to have their own uncertainty value assigned. Here is one example:

Uncertainty of Gauge Block Calibration	
Uncertainty at NIST	25 nm (1 µin)
Laboratory A	(1.8 + 0.8L) µin

Where L = distance in inches. For example when L = 1, uncertainty = 2.6 µin for Lab A.

Up to 1 inch (25mm). Larger sizes have larger uncertainties. At NIST, uncertainty for 4 inches (100 mm) is 2 µin (50 nm)

Assume *(a)* (below) is the gauge block calibrated at NIST and *(b)* is unknown block.



Contact points 1 and 8 are checked twice, as are the points 2 and 7. All four points should be within 50 nm (.000002 in) or better. If the machine fails to repeat within this limit, NG (No Good) will be flashed on the monitor screen

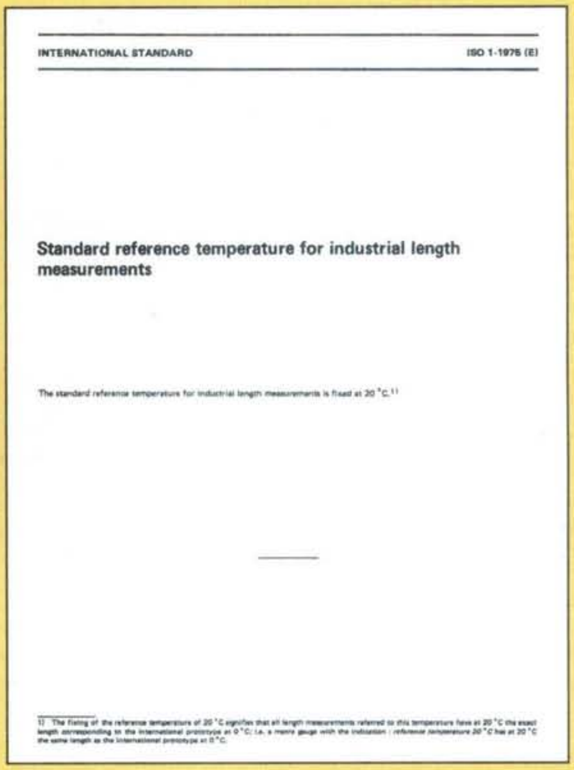
For a 1 inch gauge block the uncertainty of this lab is 2.6 µin, and for 4 inches it will be 5 µin. All in all, this laboratory's uncertainty is extremely small. Among many so called uncertainty "budgets", the temperature variation plays a significant role in this uncertainty number.

Standard Temperature for Length Measurement

This historic ISO standard at right, ISO1-1975, must be the shortest standard ever issued by any organisation. It reads "Standard reference temperature for industrial length measurement" which is the title of this standard (in bold type face). The single-line sentence in the centre reads "The standard reference temperature for industrial length measurements is fixed at 20°C."

Under the footnote in much smaller type face the text reads: "1) The fixing of the reference temperature of 20°C signifies that all length measurements referred to this temperature have at 20°C the exact length corresponding to the international prototype at 0°C; i.e. a metre gauge with the indication: reference temperature 20°C has at 20°C the same length as the international prototype at 0°C."

This footnote explains the relationship between the old and new standards. The artefact standard of metre was originally defined at 0°C, which was the prevailing standard temperature.



INTERNATIONAL STANDARD ISO 1-1975 (E)

Standard reference temperature for industrial length measurements

The standard reference temperature for industrial length measurements is fixed at 20 °C.[1]

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[1] The fixing of the reference temperature of 20 °C signifies that all length measurements referred to this temperature have at 20 °C the exact length corresponding to the international prototype at 0 °C; i.e. a metre gauge with the indication : *reference temperature 20 °C* has at 20 °C the same length as the international prototype at 0 °C.

Calibration of Check Standard for CMM is being undertaken at this laboratory in Mexico City. The standard is calibrated under 20°C by a Helium-Neon laser interferometer

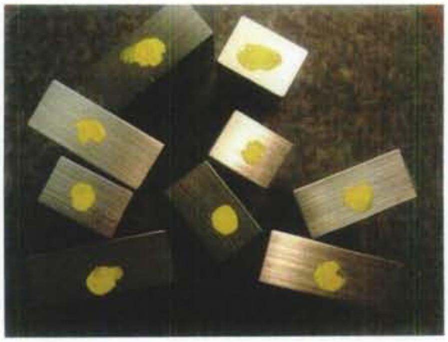
Courtesy: Mitutoyo Mexico

Worn, Rusty and Painted Gauge Blocks

At a point in time, all worn gauge blocks must be retired or replaced. Surfaces can be scratched when faced against abrasive materials. If the damage is minor, it can be blended back in. However, these examples here are beyond repair and should be replaced immediately. They are no longer the standard of length accurate up to the nanometre level.

Gauge Blocks are the most precise length standards and are placed atop the pyramid of precision. They are by and large within nanometres or a few millionths of an inch from nominal sizes in accuracy. There are three types of materials used for gauge blocks: Steel - the most popular of the three because they are the least expensive, Chrome-Carbide, and Ceramic.

Standard steel gauge blocks, such as the ones shown above, are hardened to 62 to 63 Rockwell C-scale hardness. They are heat-treated and go through sub-zero temperature treatments to stabilise their size. However, relatively speaking, they are still the softest of the three types. Ceramic gauge blocks are far more wear-resistant - roughly 10 times more than their steel counterparts. They are impervious to moisture and acid transmitted by hand, and they wring perfectly with other gauge blocks.



Nevertheless, when gauge blocks are neglected or misused, as some of the above examples show, they should be replaced or removed from the box. If the damage on a steel gauge face is minor, scratches may be removed by a fine-grained Arkansas stone. Rusty blocks should be removed from the set as well.

If retired gauge blocks are to be used for other purposes such as spacers or stoppers, a clear warning is needed to alert users as this fact. Painting a face of these blocks in red or yellow for instant ID is a practical idea. So long as the paint stays away from the gauge face, it serves its purpose.

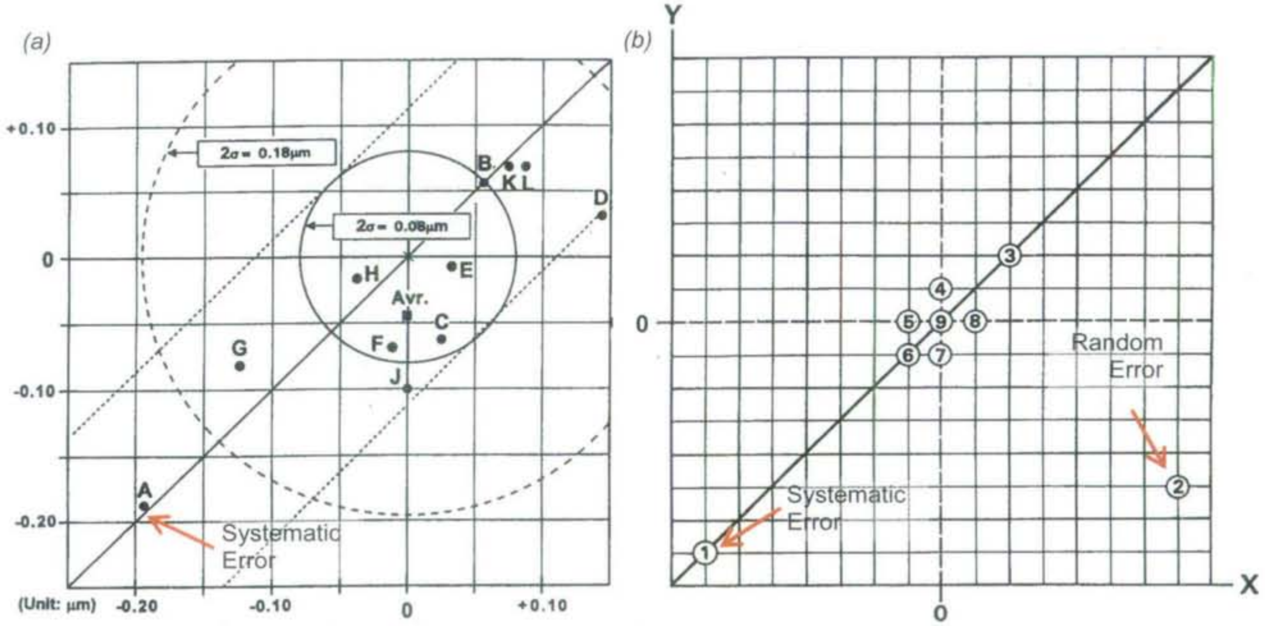
Storing and Cleaning Gauge Blocks

When they are brand new and stored in the case, the gauge blocks are covered with preservatives that prevent the mirror-finished face from coming in contact with the moisture in the air. Preservatives applied at the shipping point must be removed before use, and must be applied again if the gauge blocks are not to be used for a prolonged period.

There is a type of cleaning paper called "lint-free" wiper for laboratory use. Heavily textured surfaces allow it to pick up the dirt better than any other disposable wiper. The "lint-free" name is a misnomer as this package only claims that it is an "extra low lint wiper for clean rooms". However, any clean paper can do the cleaning job just as well, as long as it is moistened with denatured alcohol. Denatured alcohol available in hardware stores is the best cleaner for this purpose.

The cleaning process is very simple; it should not take any more than several seconds for each block. Moisten a piece of paper with denatured alcohol and place it on a flat surface, a table top for example. Remember that denatured alcohol evaporates quickly. Place the block face down and pull straight across as shown above, then flip it over to the other side. Again, pull straight while pressing it down. Repeat if necessary.

Round Robin Proficiency Test



The "Round Robin" test or proficiency test is considered to be an essential tool to validate the stated values for commercial and in-house calibration laboratories. The test is a blind test; where no one reveals the true value until all participants complete the task of assigning numbers to identical artefacts. In example *(a)* two pieces of 100 mm gauge blocks are circulated from one lab after another. Each lab plots one answer for X-axis, another one for Y-axis, called a "Youden" plot. Ideally, all laboratories in the tested group should form a tiny circle of uncertainty.

The "Youden" plot helps uncover the presence or absence of a systematic or random error. In the case of Lab A, it indicates a systematic error *(a)*. On this plot, data from one gauge block is entered on the X-axis while the other is entered on the Y-axis. They are basically the same size but may be slightly different. The fact is no one knows that at the outset. If Lab A consistently reads artefacts smaller due to their biased system, the chart will place this Lab A on the 45° line far away from the centre. This lab obviously is reading both blocks smaller — an indication of systematic error.

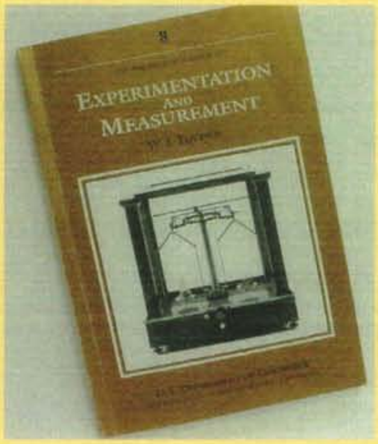
See the hypothetical example *(b)*. This is the case where a random error might exist. Look at the hypothetical Lab 2 (arrow). This lab couldn't read two artefacts closely enough with respect to all others, assuming that the "true" value lies at the centre of this chart. According to this hypothetical X-Y plot, Lab 2 displays a presence of random error, the isolated location of this point relative to others strongly suggests such trend. The other labs, except Lab 1, lie within acceptable limits.

Once the plot is released, if systematic or random error is detected, corrective action should take place. To make sure the cause of error has been identified and removed, the same artefacts may be returned for one more round and the test performed again.

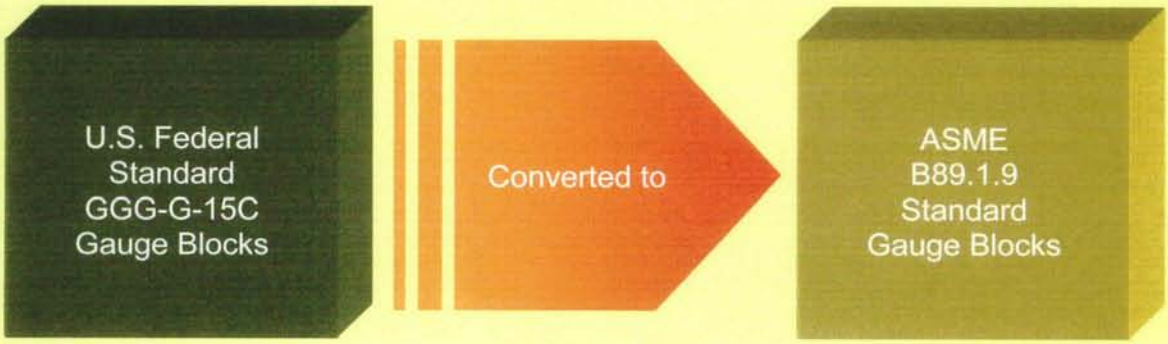
W. J. Youden (1900-1971)

William John Youden is the recognised expert in the field of statistical design of experiments. He was a statistical consultant with NBS (National Bureau of Standards) where his major interest was in the design and interpretation of experiments.

Youden was in constant demand as a speaker, teacher, columnist, and consultant on statistical matters. This book, Experimentation and Measurement, written by him is a concise and well organised reference for the average person, free of excessive mathematical equations. It is from his findings that the Youden plot system was devised.



ISO vs. ASME Standards



During the 1980s and 1990s, a conscious effort was made on the part of the standards committee members to make a transition from the U.S. Federal standard to the more international ISO standard in the spirit of globalisation.

The GGG-G-15C standard had been the standard of the U.S. for nearly 40 years, if not more. This U.S. Federal Standard was a procurement standard for the government. During the 1990s, this time-honoured standard started to make way in favour of newer ISO standard.

To embrace the spirit of ISO meant that the U.S. standards must reflect ISO specifications, for example, in gauge block specifications. There was just one small problem — the inch.

All ISO standards are written in SI (International System of Units). For length, it is the metre. From the European and Asian points of view, it poses no problem. However, there are a large number of engineers who still use inches every day. For example, to convert for the sake of conversion from inch to metric is not in the best interests of the U.S. metalworking industry. One solution is to "harmonise" or bring the numbers as close as possible between inch and metric values. In the last few years, this effort has been completed in gauge blocks with the creation of the American Society of Mechanical Engineers (ASME) B89.1.9 standard.

Chapter

9

Go/No-Go Gauges

"NOT JUST A BINARY CONCEPT"

Unlike popular belief, the Go/No-Go Gauge system is not a binary one even though the terminology strongly suggests only two states: Go or No-Go. As shown below, production parts are in actuality separated into three categories through this "binary" method.

Assume this is a production run for shafts, and the data being measured is diameter. There are two approaches for QC engineers to consider: the first one is to bring in a pair of ring gauges; one Go, the other No-Go, the second option would be to employ a variable gauge such as a micrometer and analyse the distribution. Shafts determined to be oversize will go back to the floor for additional machining, and the undersized ones will be scrapped.

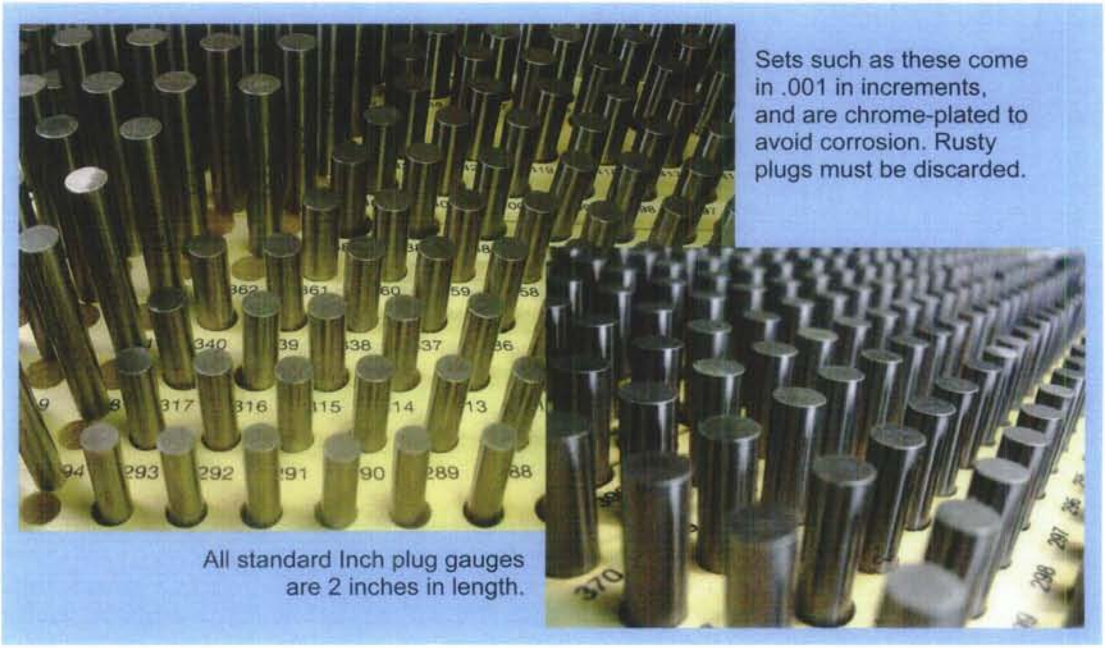
The Go/No-Go Gauge system is (a) fast and effective, (b) inexpensive to perform, and (c) requires little or no training. On the other hand, judgments tend to be subjective and may leave a grey area. For this reason, some prefer to make their Go zone intentionally narrower to safeguard the system, so that the parts will always fit into the designated area in assembly.

Within this limitation, the Go/No-Go method can be used effectively in most production runs, including final checks to verify designated functions. The Go/No-Go Gauge gave rise to the basic concept for Geometric Dimensioning and Tolerancing (GD&T): The Maximum Material Condition (MMC) in GD&T was derived from the observation of mating parts fitting together.

The Go/No-Go Gauge system is commonly seen as a binary system with only 2 states.

In reality, a production run is separated into three categories by the Go/No-Go method. Oversized shafts are returned for reworking, while the undersized shafts are scrapped.

Plug Gauges



Sets such as these come in .001 in increments, and are chrome-plated to avoid corrosion. Rusty plugs must be discarded.

All standard Inch plug gauges are 2 inches in length.

Plug gauges, pin gauges, wire gauges, feeler gauges, and other Go/No-Go Gauges are all called "functional gauges" or "fixed gauges" by most people and often "Attribute Gauges" by statistically minded engineers. "Variable Gauges" on the other hand are: calipers, height gauges, and other gauges that provide not just 0 or 1 but more variable numbers.

'-' and '+' plug gauges are available

The findings through attribute gauges are either "Go" or "No-Go", black or white, and the grey area in between cannot be judged. However, fixed gauges such as the inexpensive plug gauges, shown here, are very cost-effective tools. They qualify for the most "bang for the buck" title since they provide high accuracy yet can be obtained relatively cheaply. At left, the two types of plug gauges are presented: The minus (-) sign engraved on the plug above indicates that the plug is smaller than the indicated size by .0002 in. Similarly, the plus (+) plug below is oversized by .0002 in from the engraved value. Undersize plug gauges with the minus (-) sign are more common than their plus (+) equivalents, as they are often used to test hole sizes such as bores.

The best way to handle plug gauges is to hold them by two-fingers. There is a shop language to for this the "two-finger method", and implies the use of very little pressure. An intuitive "feel" is important for the above judgment: A little drag is allowed, but not too much.

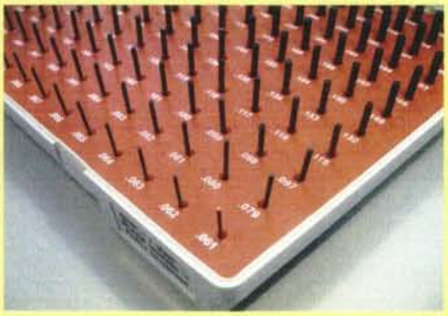
Measuring 25.4 mm (1 in) ring gauges with plug gauges only 1 μm (.000040 in) smaller than that may be the tightest clearance that can be inserted by hand. With only 1 μm clearance, it is extremely difficult to let the plug gauge slide through unless the operator has prior training. Not too many novice operators will successfully slide the plug into the bore in their first trial; it requires the axis of the plug gauge and the bore to be perfectly aligned before it will go straight through.

Courtesy: Mayer Gauge

It has been a tradition of the plug gauge manufacturers to offer their products in .001 in increments. In some cases, .001 in steps seem too large if the bore is specified with very tight tolerances. More accurate plug gauges in .0001 step are also available to cover the dimensions smaller than .001 in.

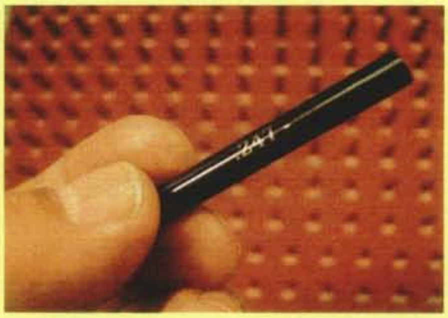
It is important to note that the operator's feel may vary. Nevertheless, an increase or decrease in size of .0001 in can provide a clearer indication of the actual size of the bore in question.

Black Oxide Plug Gauges



Entire black oxide sets are also available.

Black oxide is typically 1 to 1.5 µm (40 to 60 µin) deep. When this layer wears out, the white base metal will emerge.



All plug gauges rub against walls as they go in and out of the bore. Also, they are always handled by bare hands: This is done for better feel of the bore. As a result, they get rusty and worn. A problem is how to detect worn plug gauges, which are now smaller than when they were new. One innovation is to coat plug gauges in oxide, resulting in black plug gauges as shown above and to the right. The thickness of the black oxide is from 1 to 2 µm (40-80 µin). The black plug gauges change colour to white as the surfaces start to wear, thus providing a visual warning sign as to when they should be replaced.

The "Two Finger Method"

If both plus and minus pin/plug gauges are used, affix a sticker on the box stating "this is a minus set". Colour-coding (yellow paint on one end, for example) may be an effective way to identify that they are minus plugs. Plus plugs may be colour-coded in red, for example, to differentiate them.

Note the minus (-) sign engraved here. This indicates that the actual diameter is smaller than the nominal size by .0002 in (5 µm). Undersized 1 inch plug gauges must fit exactly into the 1 inch inside diameter as shown. The plug should not fall out freely without dragging.

Taper bearing for automotive application being tested by a plug gauge

The "Two-Finger Method" does not necessarily mean what it implies literally, but in actuality refers to using a light touch when inserting the plug gauge into the bore. How light is difficult to tell, and is learnt through experience, since the force required differs from situation to situation due to factors such as larger contact areas. In general, a "free-fall" condition where a plug gauge drops straight out of the bore is no good, implying that the plug is far too small. If this happens the next larger size should be tried. Take an undersize straight plug and practice how to use it, noting the "feel" as it enters a ring gauge of the same size. One operator's judgment, while biased a little, should not be very different from that of others; personal bias, if any, should be minimised.

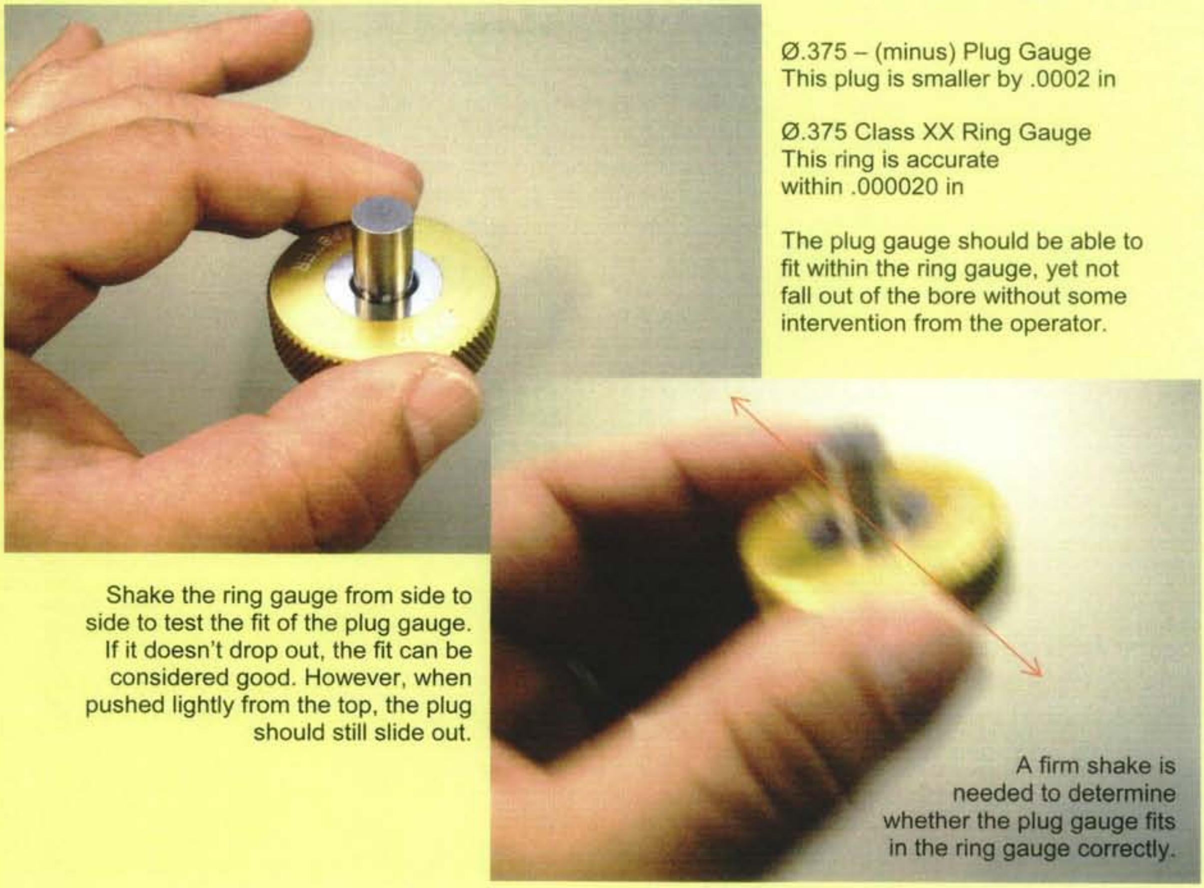
Plug gauges should enter the bore smoothly. A little drag is permissible, so long as it does not bind or freeze. First, slide it in, and then slide it out again. Turn the plug gauge 180° and repeat the previous step, keeping in mind whether there is a difference in "feel". This is the subjective part of the Go/No-Go judgment, and an operator should pay attention to it. To overcome any variation in judgment, all operators must consistently agree on what constitutes "Go" or "No-Go".

Alternative to Plug Gauges: Ball Gauges

A ball gauge is easier to put into a bore than a plug gauge of the same size. More information on page 115

Another factor to consider is the size of the plug gauge or workpiece. The heavier one should stay on the table with the lighter one will be inserted onto it, simply because it is easier that way.

The best way to keep plug gauges ready is to put all of them back into the case at the end of the day. Popular sizes go missing easily on the shop floor. If both plus and minus plug gauge sets are to be used under one roof, it is recommended to paint one end of each set different colours. Although this method is not suggested in books, it is effective improvisation that works well on the shop floor.



Ø.375 – (minus) Plug Gauge
This plug is smaller by .0002 in

Ø.375 Class XX Ring Gauge
This ring is accurate within .000020 in

The plug gauge should be able to fit within the ring gauge, yet not fall out of the bore without some intervention from the operator.

Shake the ring gauge from side to side to test the fit of the plug gauge. If it doesn't drop out, the fit can be considered good. However, when pushed lightly from the top, the plug should still slide out.

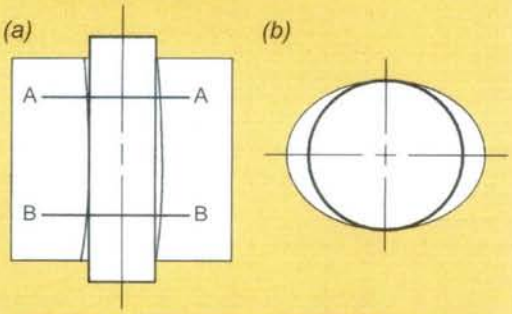
A firm shake is needed to determine whether the plug gauge fits in the ring gauge correctly.

The judgment of "Go" or "No-Go" using plug gauges depends on the "feel" of the operator. This is the reason why Go/No-Go Gauges are subjective to a degree. They do not yield a number, other than 0 or 1, the essence of attribute gauges.

In spite of that, a threshold can be established within this limitation. As shown above, the plug should not simply fall out from the bore. If it does, the plug is too small and one must choose the next larger size. If that does not go in, we can be sure that the diameter should be somewhere between the two. In the inch system, each step is normally .001 in, but the plug gauge suppliers also make specials: specific intervals can be split from .001 inch into 10 parts, to .0001 in (see page 111).

More importantly, the merit of plug gauges is that they can check what bore gauges cannot. Both plug and bore gauges may be used in tandem to supplement each other, especially when a mating part is expected to come through. In fact, most bores expect mating parts (e.g. Bolt Circle).

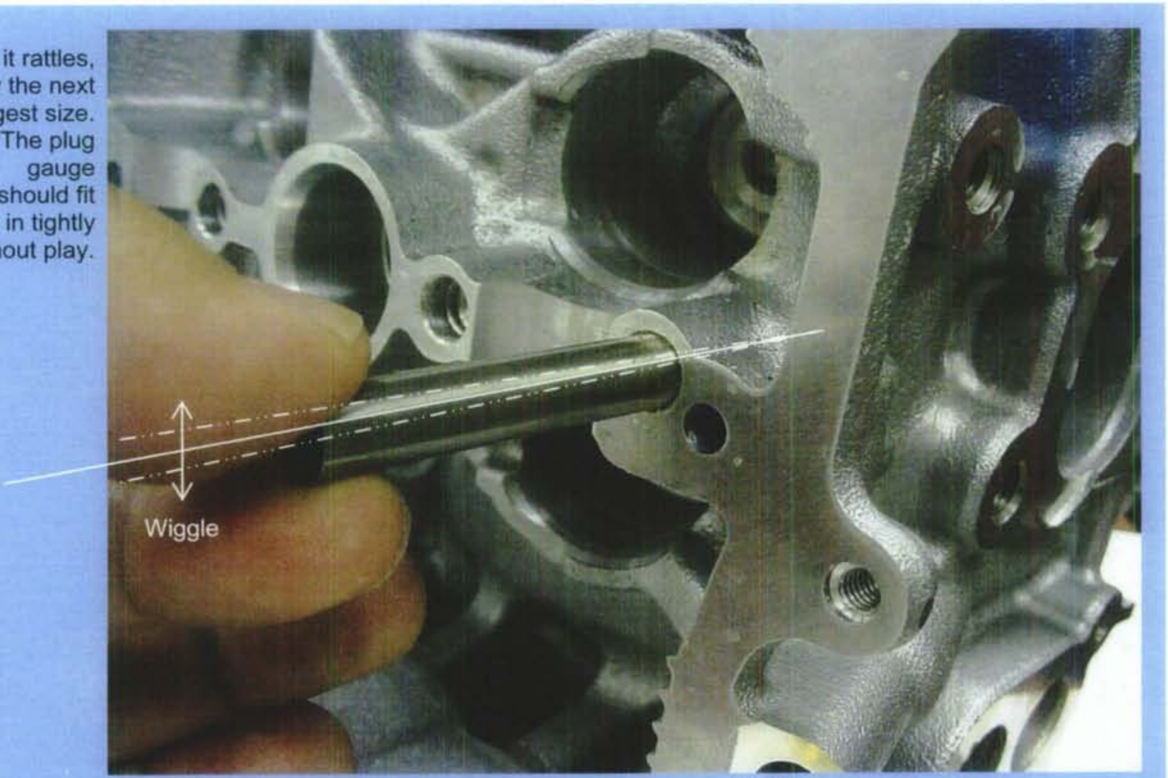
Measuring curved bores

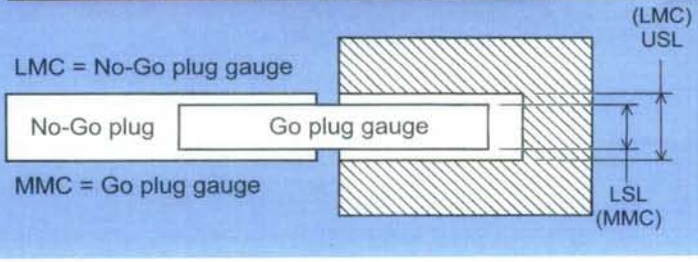


Assume a bore gauge measured the inside diameter A-A and B-B *(a)*. Note, A-A and B-B are independent slices of the same bore. Some call these measurement "local size" which cannot represent the total cylinder, whereas the plug gauge will detect the worst-case condition, *(b)* above. Plug gauges will reflect the smallest inside diameter.

Checking the Function of a Blind Hole

If it rattles, try the next largest size. The plug gauge should fit in tightly without play.





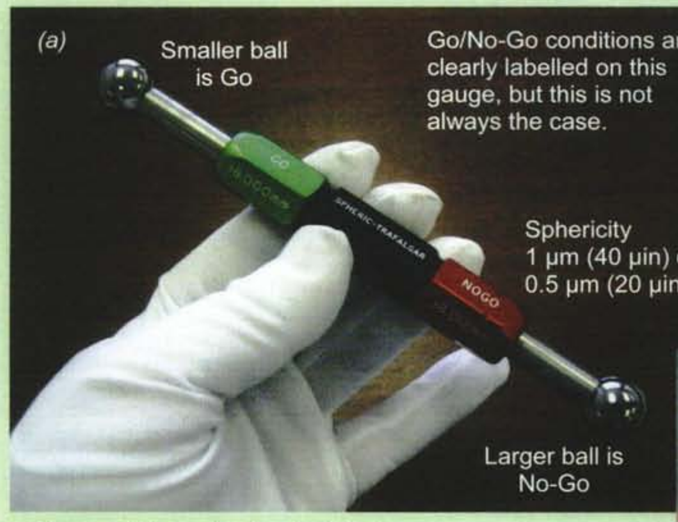
The Go plug must fit into the bore at its LSL (Lower Spec Limit), which is also at MMC (Maximum Material Condition). The No-Go plug gauge must not go into the bore at its USL (Upper Spec Limit).

The centre coordinates of this blind hole, relative to datum in this aluminium engine block should be specified on the blueprints. Being an automotive product it would be in CAD. Of the most used callouts "true position" (now changed to "position") may be called for. The best and the fastest way to validate the positional accuracy will be to use the CMM.

While the exact size and location of this hole can be quickly found by a CMM, it is still a good practice to check the hole size with a pin gauge and evaluate the function of this particular bore, which is to accept an incoming rod at assembly.

The "worst condition" in fit in this example is a combination of the smallest bore and the largest rod, both within the respective limits of size. Assuming this is a classic case of clearance fit, the question is how to validate the functional requirements of the bore. A pin gauge representing the mating part at its Maximum Material Condition (MMC) — the largest rod diameter within the limits of size — will be an effective method to check the clearance.

Ball Gauges



For bores "Go" is the lower size limit, or Maximum Material Condition (MMC) of the bore, and for that reason the smaller ball is "Go" gauge, larger one is "No-Go."

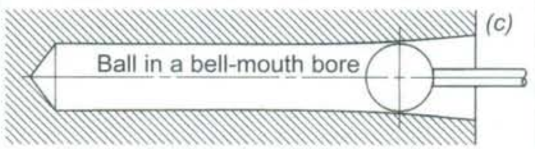
Courtesy: Spheric-Trafalgar Ltd.

A Reversible Go/No-Go Ball Gauge

Ball type Go/No-Go Gauge is easier to handle for thin work-pieces such as this example.

When presented with 2 different sized ball gauges to measure a bore, a common question is "which one is the Go gauge?" This can be easily answered by observing the above examples *(a)* and *(b)*. In the first case *(a)*, the upper limit for of the bore is Ø18.012 mm and the lower limit is Ø18.00 mm. This is a classic case for bore diameters where they can be bigger, in this case Ø18 mm by 12 µm (.0005 in) but cannot be smaller than Ø18 mm because a shaft is expected to come through. Assume the bore is Ø 18.006 mm — right about the middle of the tolerance zone. The Ø18.000 mm Go gauge should go through a properly sized bore. Flip the ball and try Ø18.012 No-Go gauge; this larger gauge should not enter the bore, implying that the bore is within the upper and lower limits. In the Go/No-Go gauge system, the exact size cannot be judged: for precise sizes, a dial or digital bore gauge will be required.

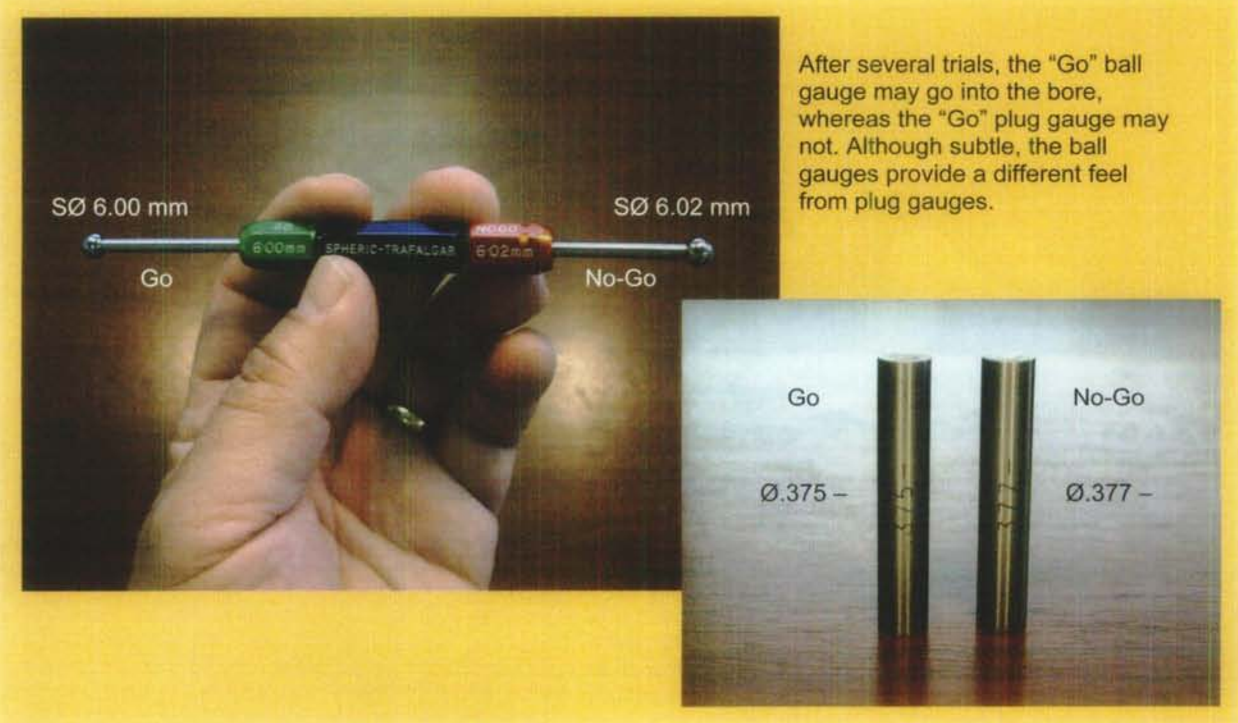
See the drawing *(c)* at left. One drawback of the common plug gauge is that it is insensitive to a bell-mouth hole, whereas a ball gauge of the correct size is likely to detect such imperfections. The judgment may be slightly subjective, but it can clearly indicate the presence or absence of a bell mouth. On the other hand, the ball gauge cannot detect a curved bore because it is not a cylinder (see example on previous page).



Ball gauges can detect the bell-mouth condition, which plug gauges cannot.

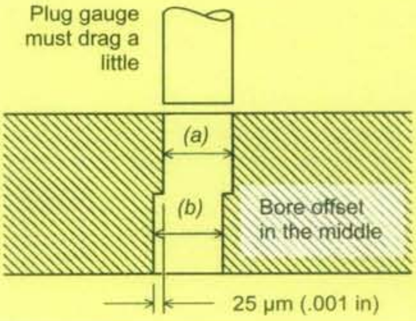
Note, dial or digital bore gauges measure inside diameters, but what they represent is a "local" size and the measured data cannot represent the entire cylinder. Plug gauges will be the answer to that.

Selecting Go/No-Go Gauges



After several trials, the "Go" ball gauge may go into the bore, whereas the "Go" plug gauge may not. Although subtle, the ball gauges provide a different feel from plug gauges.

There is one simple answer to this often asked question. For those who learned GD&T, Maximum Material Condition (MMC) of a bore or MMC of a shaft is the "Go". As a general rule, the smallest diameter of a bore allows the Maximum *amount of* Material Condition (MMC). Assume a bore is specified with the upper size limit of Ø6.02 mm and the lower size limit of Ø6.00 mm. If the bore in question is Ø6.00 mm, the maximum *amount of* material was used. This is MMC: therefore "Go" belongs to Ø6.00 mm.



When the internal wall is coarse, or the bore is shifted in the middle as implied above, the bore gauge will measure the location *(a)* and *(b)* and report the bore diameter is OK. *(a)* or *(b)* however cannot represent the entire geometry. Only the plug gauge will give the right answer.

The situation is reversed for an unknown shaft. A pair of ring gauges will be typically used. When ordered in pair for Go/No-Go purposes, the supplier will put a groove on the No-Go ring (see page 118). The Maximum Material Condition of a shaft is when it is the largest within the limits of size. The largest size for a shaft is MMC, and that MMC is Go. Inside or outside, MMC always means Go for Go/No-Go Gauge. In order to avoid confusion, ring gauges for Go/No-Go application are not entered here.

Assume that a bore is specified as Ø.375 (3/8 in), and allowed to be larger than that by .002 in. Apply the rule that the Maximum Material Condition (MMC) is the smaller bore where more *amount of* material is used. For this reason Ø.375 is "Go" and Ø.377 is "No-Go".

Ring Gauges

Engraved "XX" indicates that the accuracy of this 1 in ring gauge is .000030 in (0.75 µm).

Class-XX (Double X) ring gauges are considered by many to be accurate enough to set most bore gauges having 1µm (.00005 in) resolution. Class XX and XXX ring gauges are considered as standards whereas Class X (Single X) and below are mainly for Go/No-Go applications. Class-XXX ring gauges are the most accurate of all, and this group should be treated as "master" ring gauges. Some ring gauges are chrome-plated; the thickness of such plating is usually 70 µm (.003 in) or more. Undoubtedly, chrome-plated ring gauges last longer.

Six Different Grades of Ring Gauges

Sizes above & inclusive (Inch & Metric)	Standard to set bore gauges		For Go/No-Go applications only			
	Class-XXX	Class-XX	Class-X	Class-Y	Class-Z	Class-ZZ
.010 to .825 in 0.254 to 20.95 mm	.000010 in 0.25 µm	.000020 in 0.5 µm	.000040 in 1 µm	.000070 in 1.75 µm	.0001 in 2.5 µm	.0002 in 5 µm
.825 to 1.510 in 20.95 to 38.35 mm	.000015 in 0.38 µm	.000030 in 0.75 µm	.000060 in 1.5 µm	.000090 in 2.25 µm	.00012 in 3 µm	.00024 in 6 µm
1.1510 to 2.510 in 38.35 to 63.75 mm	.000020 in 0.5 µm	.000040 in 1 µm	.000080 in 2 µm	.00012 in 3 µm	.00016 in 4 µm	.00032 in 8 µm
2.1510 to 4.510 in 63.75 to 114.55 mm	.000025 in 0.63 µm	.000050 in 1.25 µm	.0001 in 2.5 µm	.00015 in 3.75 µm	.0002 in 5 µm	.0004 in 10 µm

Class-XXX and XX ring gauges are considered as standard grade to which bore gauges can be calibrated against. They are not to be confused with Go/No-Go purpose ring gauges where Class-X would be sufficient for the purpose. Class Z is a popular grade also for Go/No-Go applications.

Thread Ring Gauges

A set of Go/No-Go thread ring gauges

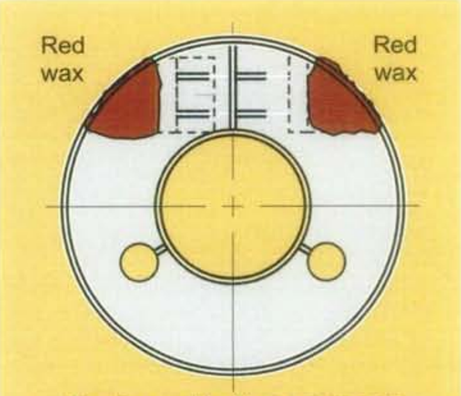
UNEF 2A
For unified (60°) extra-fine class 2A threads.

LOPD (Low Pitch Diameter)

On other gauge: GOPD (Go Pitch Diameter)

As a general rule, everything external is easy to check, and everything internal is much harder. This thread ring gauge checks the pitch and fit of external threads. This particular example is for 7/8-20, or 20 threads per inch, with 7/8 as the nominal pitch diameter. Go and No-Go thread rings bear the same identification, but one is for Go and the other one is made intentionally out of pitch, or smaller for No-Go. In this example, "Go" pitch diameter is set at .8412 and "No-Go" at .8368 in.

Thread ring gauges are variable in pitch, and are designed to be preset by a qualified specialist. Green or red sealing wax over the adjusting screws are used to clearly identify which one is Go and which is No-Go, and also prevents tampering. If the wax is broken or missing, do not use the gauge, and consult the QC supervisor.



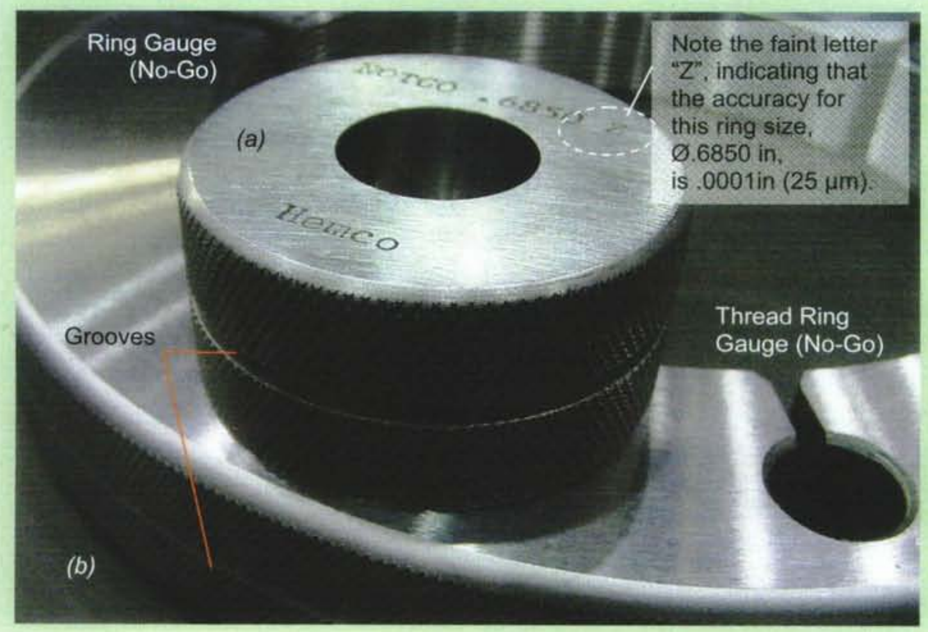
Turning and locking screws are sealed by wax to prevent tampering.

A threaded part will first be tested on the "Go" ring and inserted through its entire length. It must go through tight but firmly. Unlike straight ring gauges, the thread rings feel much tighter because of the larger surface area in contact. "Smooth" may not be an appropriate adjective here, but "firm" is more accurate in describing the feel.

After completing the Go test, try the No-Go ring. The threaded part should not go any more than one-and-a-half turns (sometimes up to three turns), and should freeze at that point. At that stage, do not apply any more force and unscrew the part.

When not in use, always place it face down, lest it roll on the bench and hit the floor, affecting the original settings. Also, do not toss it or drop it.

No-Go Ring and Thread Ring Gauges

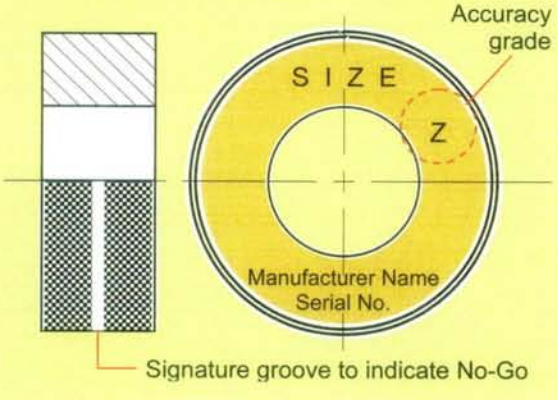


A pair of No-Go gauges. The groove will be added when a pair of ring gauges or thread rings is ordered for Go/No-Go application.

Courtesy: Hemco

A pair of Ring Gauges, each representing USL (Upper Specification Limit) and LSL limit is used for Go/No-Go gauging purposes to separate shafts for example into three groups: Oversize, Go, and Undersize. These attribute gauges are made to blueprint specifications, and are only used for the intended production run. The thread ring gauge with grooves on its circumference is intentionally made not to fit by selecting wrong thread pitch.

No-Go ring gauges *(a)* and No-Go thread ring gauges *(b)* are identified with a single groove cut around the entire circumference of the ring. Go rings are identified as not having this groove, allowing pairs of Go/No-Go gauges to be differentiated. Which grade to use is also an issue: When the user is uncertain as to which one to choose, the supplier will send a single X grade, which is generally good enough for Go/No-Go applications.

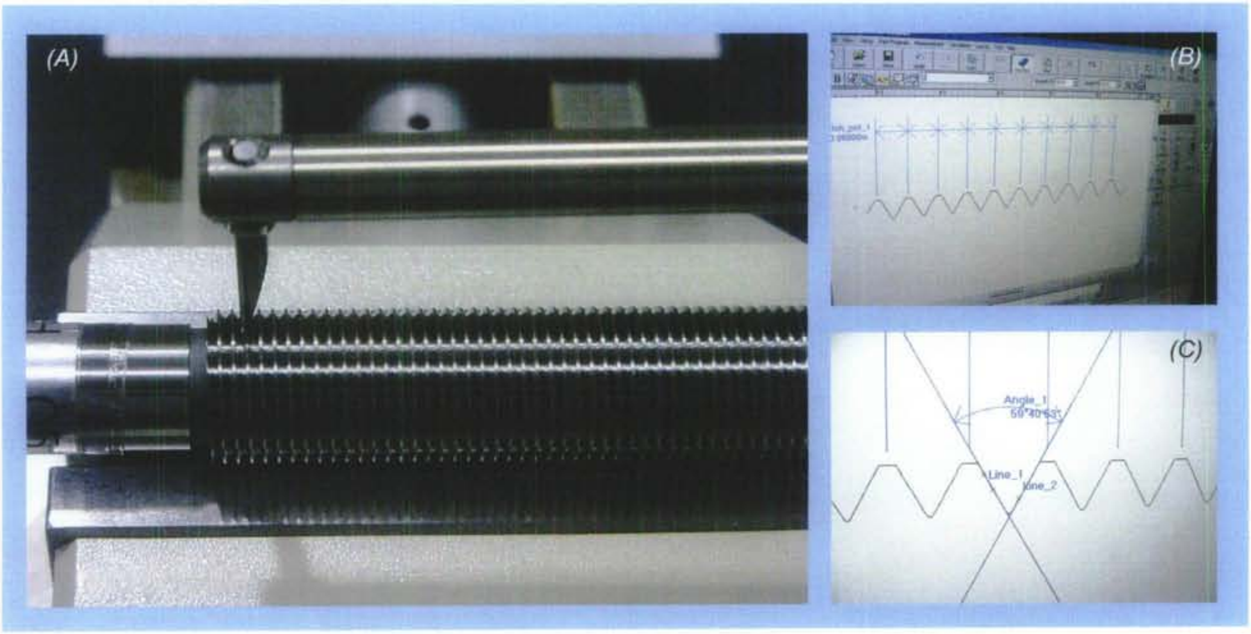


Ring gauges can only check size. If a shaft is Ø10 mm and 100 mm long (1 to 10, diameter to length ratio), the straightness may need to be checked. However, ring gauges are for diameter only and will not check straightness.

If a shaft is specified with a tight cylindricity callout, the ring gauge will not help either. A roundness testing machine is required to check cylindricity. However, check to make sure the shaft meets size limits first before checking cylindricity.

Both micrometers and ring gauges should be used for measuring shaft diameters: micrometer for size, ring gauge for function.

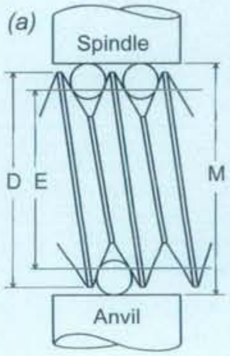
Screw Threads



The functionality of male threads is checked by thread rings, and female threads are checked by thread plug. Thread rings are against the thread plug by, among others, the three-wire method as shown in the drawing *(a)* below. The thread profile can be inspected by Profile Projector or by using a probe and tracing the entire profile as in *(A)*.

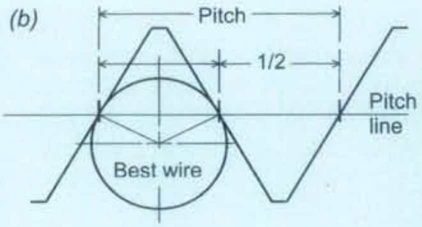
The monitor screen allows the traced line to be zoomed in and out for closer observation, *(B)* and *(C)*, and software for this type of instrument enhances the inspector's ability to check many configurations. It is when the female threads are presented the only choice – unless they are cut open in half – is to have a probe and trace the internal profile and then magnify.

The illustration below *(a)* is a typical example of a single-thread screw. There are a variety of methods to check profile, contour, lead, and other related elements for male threads.



Pitch diameter is the most critical and is usually measured by a set of three wires. The best wire in terms of wire diameter is the one that make contact with the pitch line *(b)*. For standard 60° threads, the best wire (W) is given as follows:

W = 0.57735 x pitch



Pitch line is the Imaginary line where 1/2 of such line will cut through the thread and 1/2 of the line will go through open space.

The size of best wire can be calculated, but the wire must be of the best quality as well. In most cases, the cylindricity of wire is 1 μm (.000040 in). Two wires are inserted at one side and one on the other between the micrometer's spindle and anvil as illustrated in the drawing *(a)*. The following formula shows how to work out the pitch diameter.

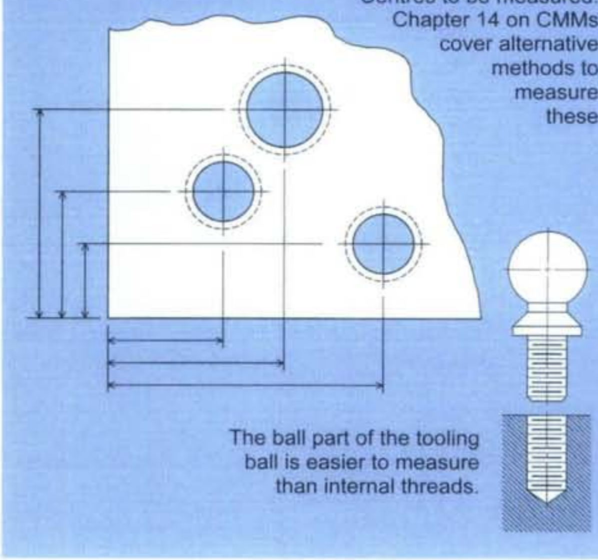
E = M – (3 x W) + (0.866025 x P)

E = Pitch DIA / M = Measurement / W = Wire / P = Pitch

Tooling Balls

Courtesy: Spheric-Trafalgar Ltd.

Tooling balls are made of stainless steel or tungsten carbide. Coaxiality between the ball and stem is less than 5 µm (.0002in) according to the supplier. Note: this tooling ball is made of two separate parts: ball *(a)* and stem *(b)*.



Centres to be measured: Chapter 14 on CMMs cover alternative methods to measure these

The ball part of the tooling ball is easier to measure than internal threads.

Threaded hole centres are hard to find. Many CMM operators use a variety of ways to estimate the centre coordinates. With a standard touch probe (described below), CMMs produce close but not precise enough results. The solution for this should be to use tooling balls. Comprised of a stainless or tungsten carbide ball attached to a threaded stem, they are manufactured with coaxiality of less than 5 µm. Insert one into the threaded holes, then measure the ball to get the centre coordinates. This method takes time, and more cumbersome than simply touching the threaded hole with a ball probe. The trade-off in the extra time spent by using these tooling balls is that the resulting coordinates would be much more precise. When location tolerances are tight, this method may be the most suitable.

Checking Depth of Threads

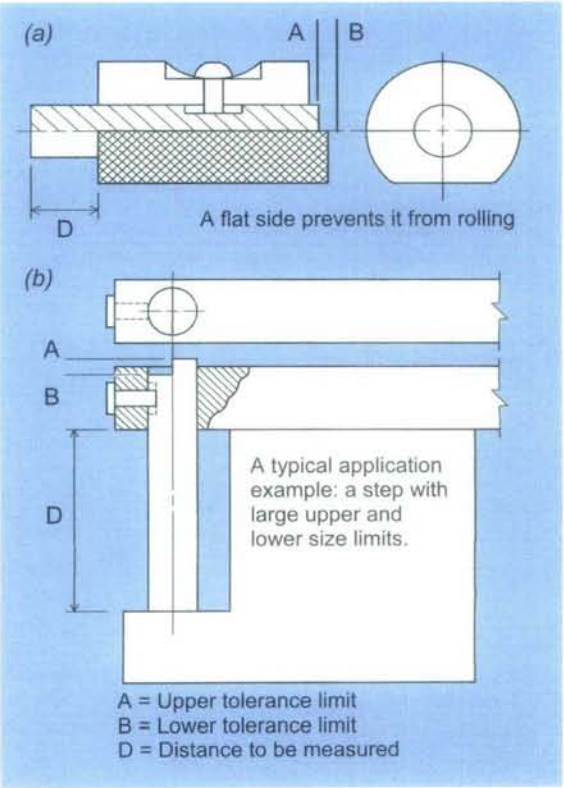
CMM Probe

Contact Probe

How far threads are cut is hard to check for deep blind holes, where bisecting the part or using threaded plug gauges are not practical.

Not enough threads invite failures. A special probe for CMM shown here is designed to check the depth of threads. It consists of a long finger to reach down to the depths of threaded holes. By dragging the finger, the probe can detect whether or not the tap reached the bottom.

Flush Pin Gauges



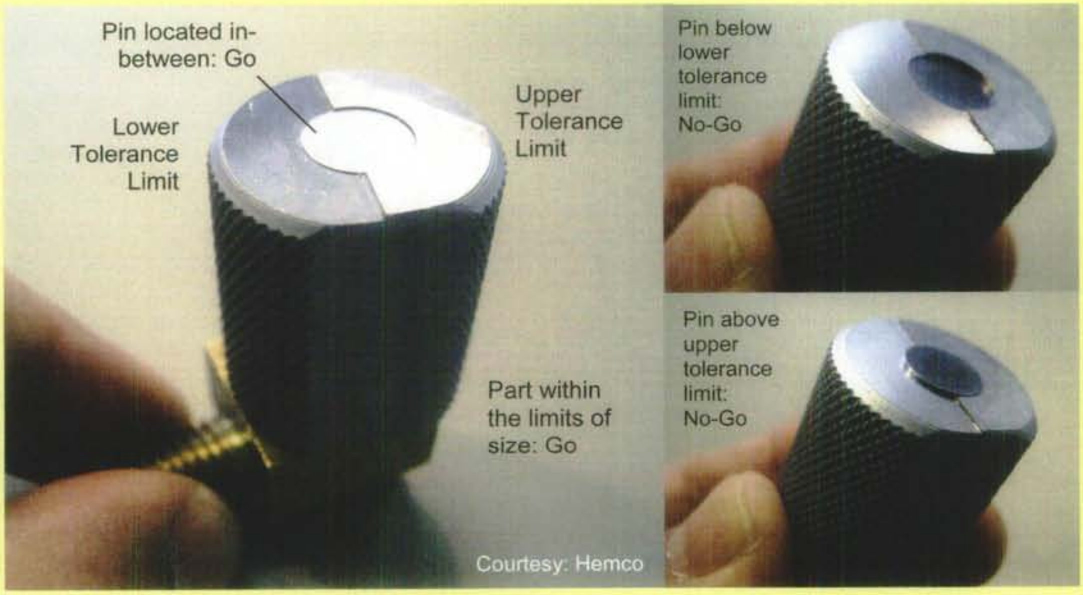
Categorically speaking, there are two methods to check the depth of a workpiece: one is by attribute gauge; the other is to use the variable gauge such as a depth micrometer.

When the tolerance is large enough, for example 0.05 mm (.020 in) or larger, the Go/No-Go method may be used effectively. Go/No-Go method will separate an unknown lot into three groups: No-Go (Oversize), Go, and No-Go (Undersize), as shown on the first page of this chapter, page 109. A specific range of Go/No-Go gauges, the Flush pin gauge, is most often used to check steps or depths having large tolerances, large enough to see or feel steps with a thumbnail (hence the nickname "thumbnail gauge") or a pencil.

There are 2 varieties of this gauge: One has a moving pin with a flat top and a reference top has two steps as in example *(a)*, and below. The pin must stay below the top land (the upper tolerance limit) and above the bottom land (the lower tolerance limit). If it does, as in this case, the part checked is within the two limits and therefore "Go".

The other type is simply an inversion of this, where the moving pin is featured with two steps, the top of which should be above and the bottom should be below the bars' top surface. See illustration *(b)* on this page.

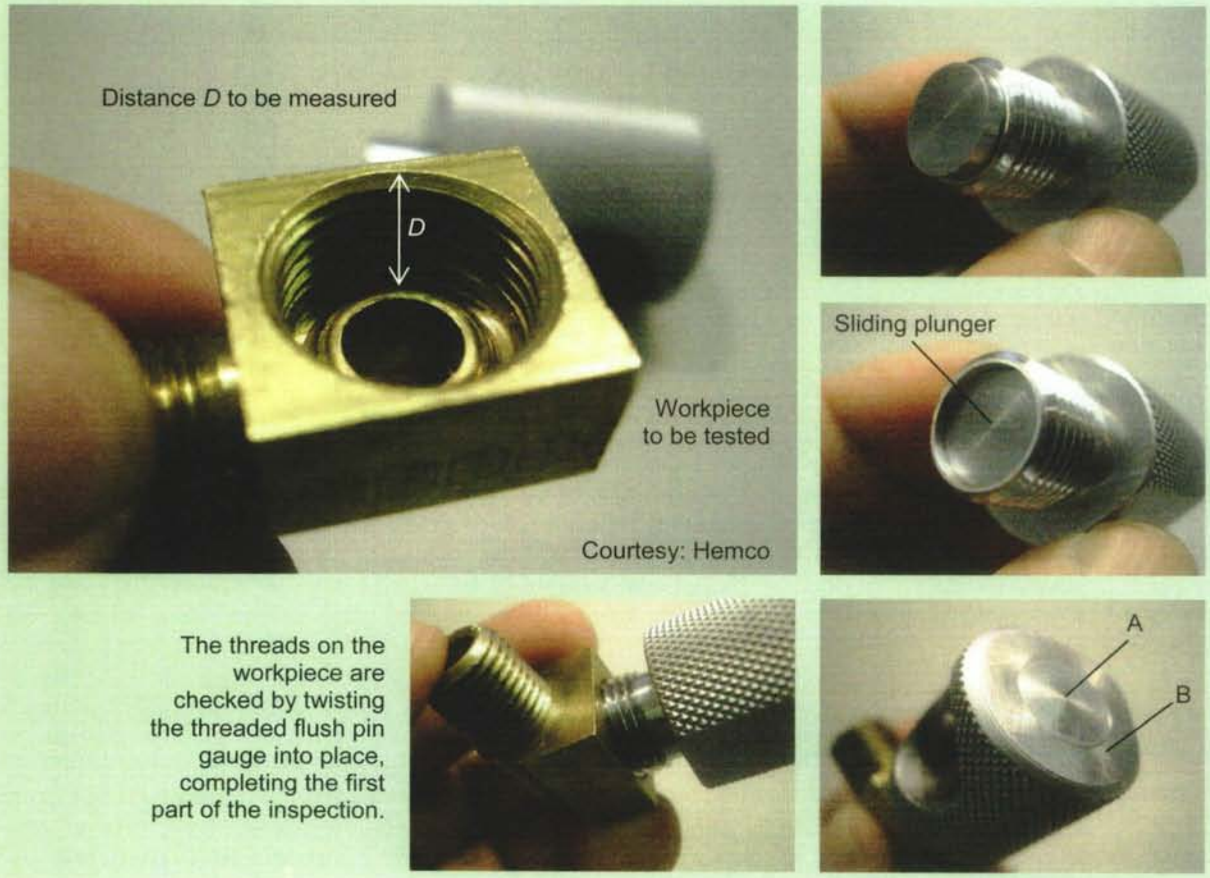
The ease of Go/No-Go judgment diminishes as the tolerance gets smaller. It is important that it must remain large enough such that judgments by different personnel will not conflict.



Courtesy: Hemco

This Flush Pin Gauge is based on the type *(a)* above

Threaded Flush Pin Gauge

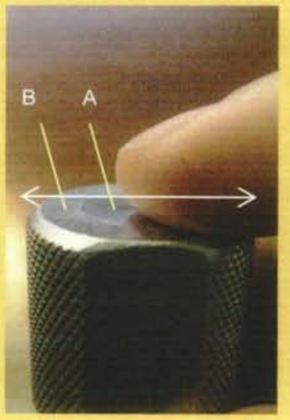


The threads on the workpiece are checked by twisting the threaded flush pin gauge into place, completing the first part of the inspection.

The special gauge introduced on this page combines two inspections into one: A flush pin gauge to check the depth and a thread check as a threaded mating part is inserted. Unlike the straightforward and widely used design shown on the facing page, this Go/No-Go Gauge features a flat surface on both vertically moving centre plunger A and the top land B.

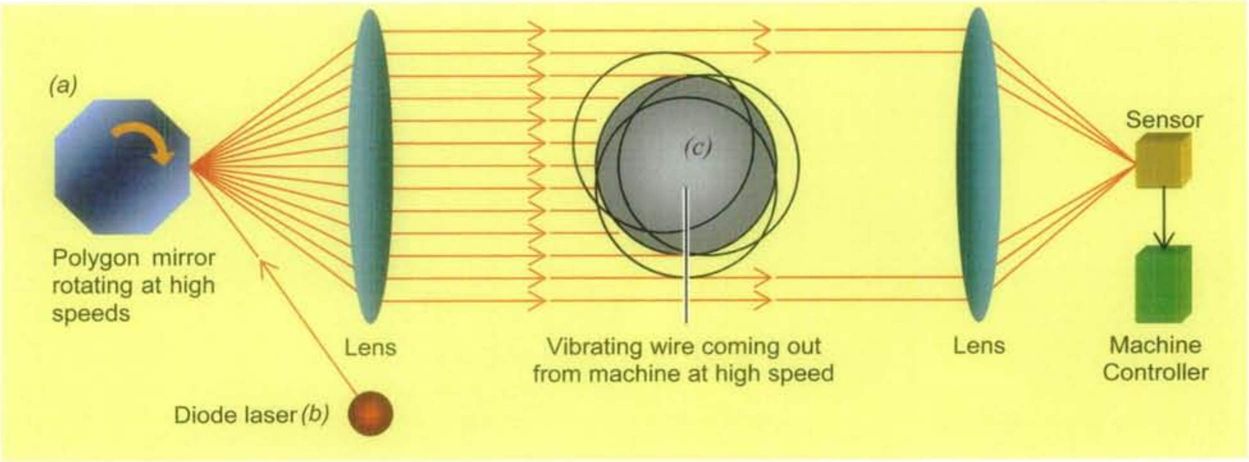
If the two surfaces A and B are properly aligned, when touched by hand they will feel as if they are made of one piece. When out of alignment, a gap as small as 50 µm (.002 in) can be immediately recognised. It will be clear which one is higher than the other.

Functional gauges of this type check whether or not the mating part will fit into the feature provided at assembly. What it does not provide is how small or large, for which a variable gauge must be employed. However, that approach requires time-consuming techniques, justifying that within this limitation, if the Go/No-Go method is designed and executed properly, it is the quickest way to check a large number of parts in a bin.

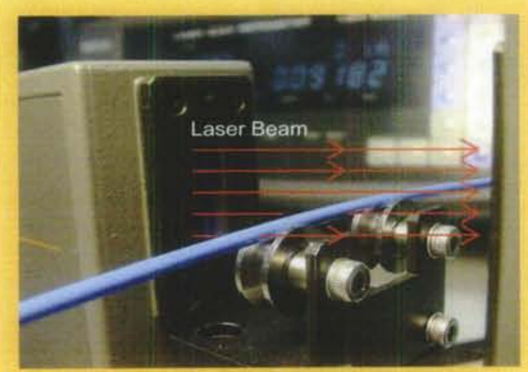


One should be able to distinguish 25 µm (.001 in) by touch and visual inspection. When checked by a gauge such as a test indicator, the gap will be revealed more accurately. The assumption here is that the gauge is not required.

Laser Scan Micrometer



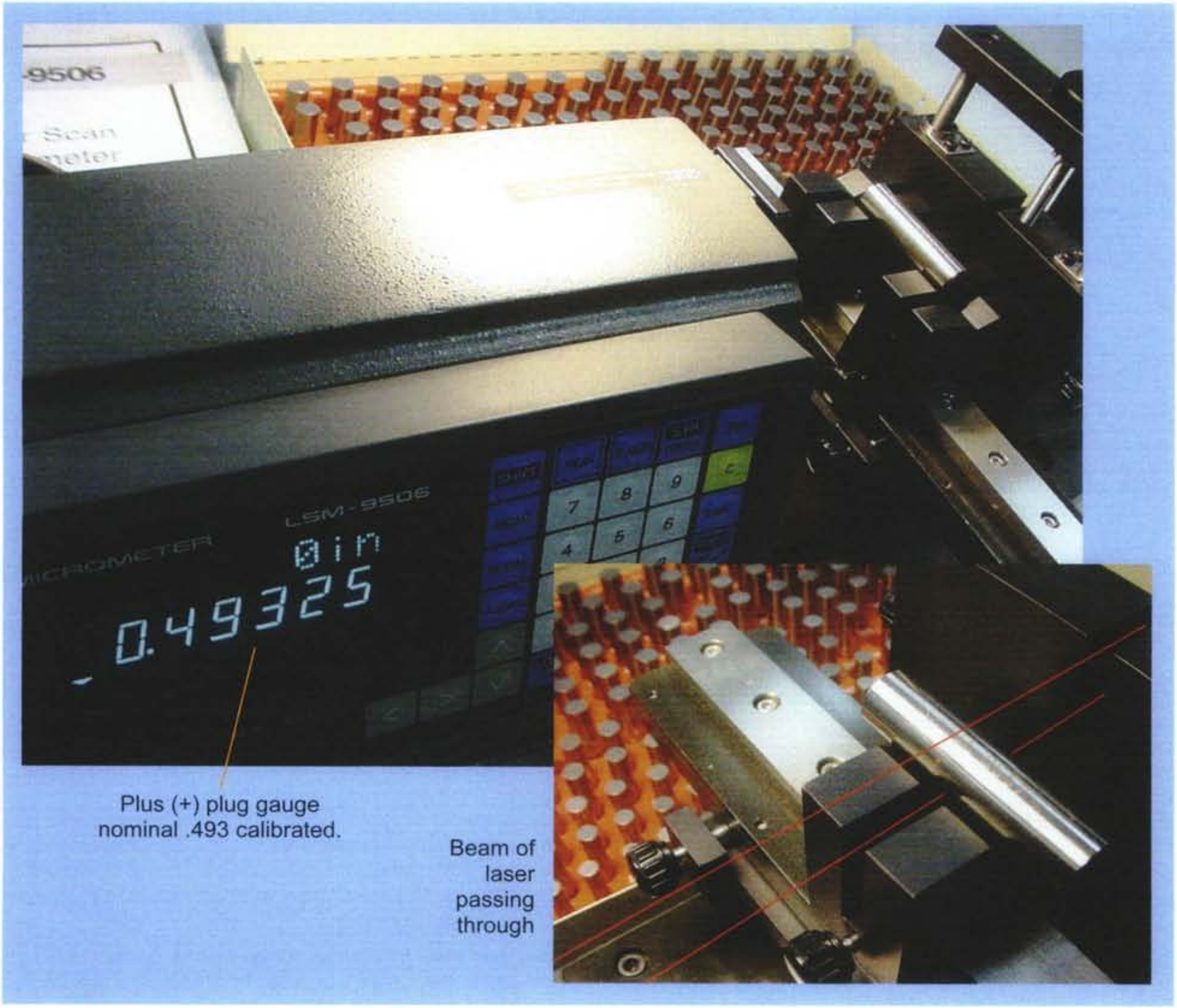
The invention of the laser was certainly one of the most significant events of the last century. The scanning laser micrometer described here takes full advantage of the characteristics of laser, which is collimated, coherent beam. Among varieties of laser available, some used in defence, the most widely available in metrology is the least harmful of all: The Helium-Neon laser. The Laser Scan Micrometer employs a tiny laser diode *(b)*, smaller than a fingernail, from which a red laser beam emerges.



This detecting method was originally developed during the 1970s for wire producing machinery where the diameter of a fast-moving wire must be controlled continuously while wire is coming out of the machine. As the wire would be vibrating and moving at high speeds, contact methods were not practical in this application. A non-contact method had to be devised.

See the illustration above. If the polygon mirror *(a)* reflecting the laser beam rotates at 3600 rpm, for example, then it will rotate 60 times per second. What if a polygon mirror, having eight facets, can be installed instead of a single reflecting mirror? Then 480 scanning cycles per second may be achieved. The speed of motor can be made faster, and the mirror may possess even more faces. At that high scanning rate, the object passing under the beam may be captured and measured as if the wire were motionless.

Scanning at a speed of 1600 times per second, the vibrating wire *(c)* can move even faster. The gauge detects the time elapsed as laser cut across the wire from one edge to the other. The primary source of detection is time, not length, which is translated into the physical dimension with resolution as small as 0.1 μm (.000005 in).



Plus (+) plug gauge nominal .493 calibrated.

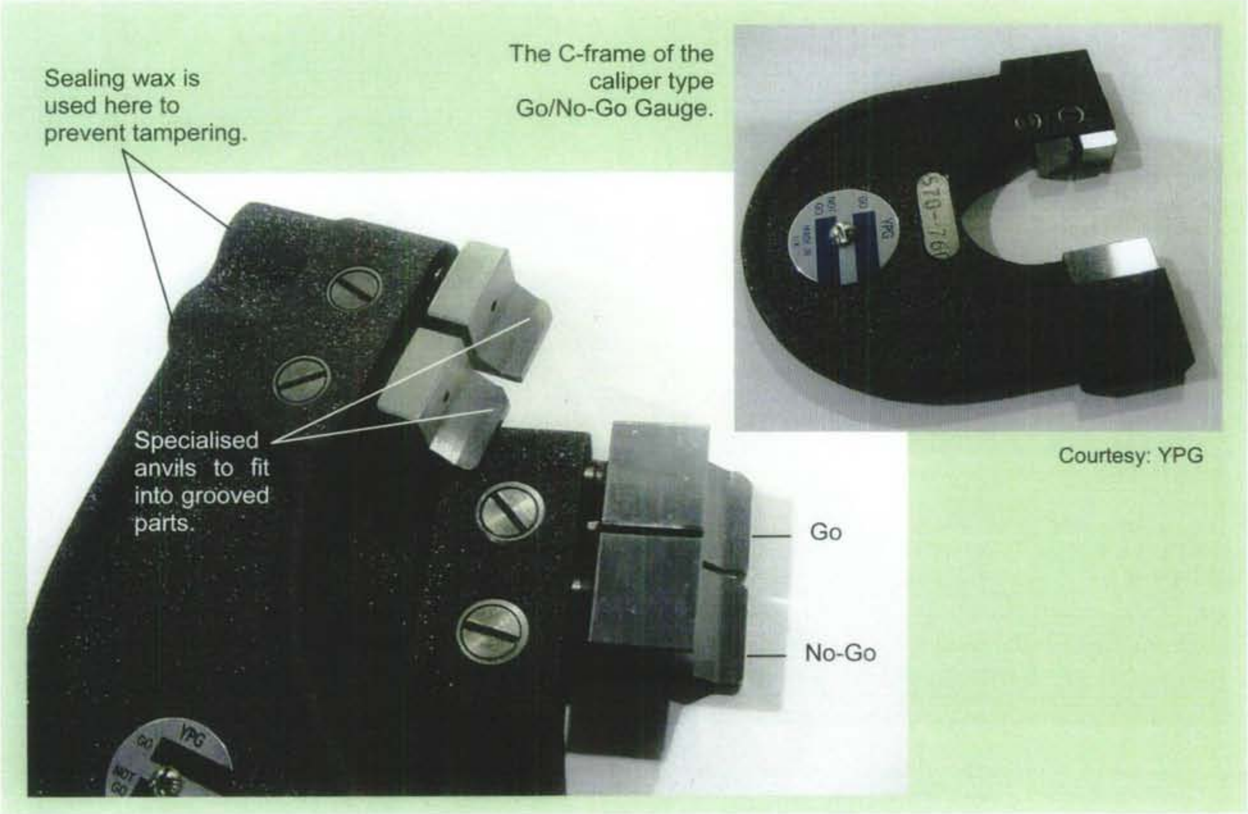
Beam of laser passing through

Pin or plug gauge sets are supplied in either plus (+) or minus (-) .0002 from the nominal size. If these two sets coexist in one plant, the plug may be colour-coded or a large sign may be affixed on the box warning what they are. Individual sizes are engraved on the plug surface, but over time the gauges themselves may change in dimensions due to wear. Therefore calibration is necessary from time to time.

Plug gauges are not to be calibrated by an ordinary micrometer, for both are nearly equal in accuracy and the "4 to 1" rule in calibration is not present. One way to overcome this deficiency is to use the laser scan micrometer. With this system, calibrating one plug gauge takes only a few seconds. The calibration data can be automatically downloaded to any gauge control system in-house. Without this system, plug gauges may be placed flat adjacent to a gauge block and be compared by a LVDT probe.

The set shown above is the plus (+) set. When checked against the beam of the laser, the digital display of the Laser Scan Micrometer indicated .49325 in, where the engraving was .493 in. The last digit may go either to 0 or 5, so disregard the last digit (Note this is an unknown inherent in all digital displays). When the plug was pushed in and rotated, the number should remain the same.

Caliper Type Go/No-Go Gauge

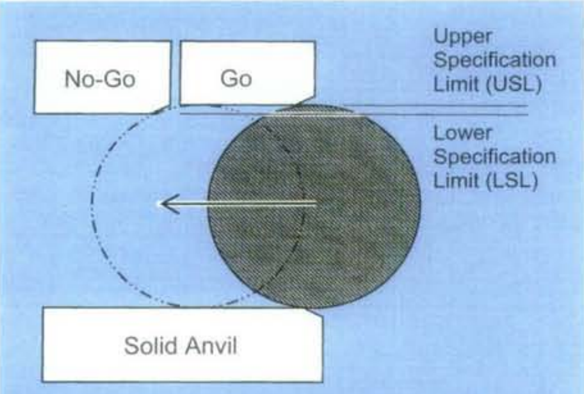


Sealing wax is used here to prevent tampering.

The C-frame of the caliper type Go/No-Go Gauge.

Specialised anvils to fit into grooved parts.

Courtesy: YPG



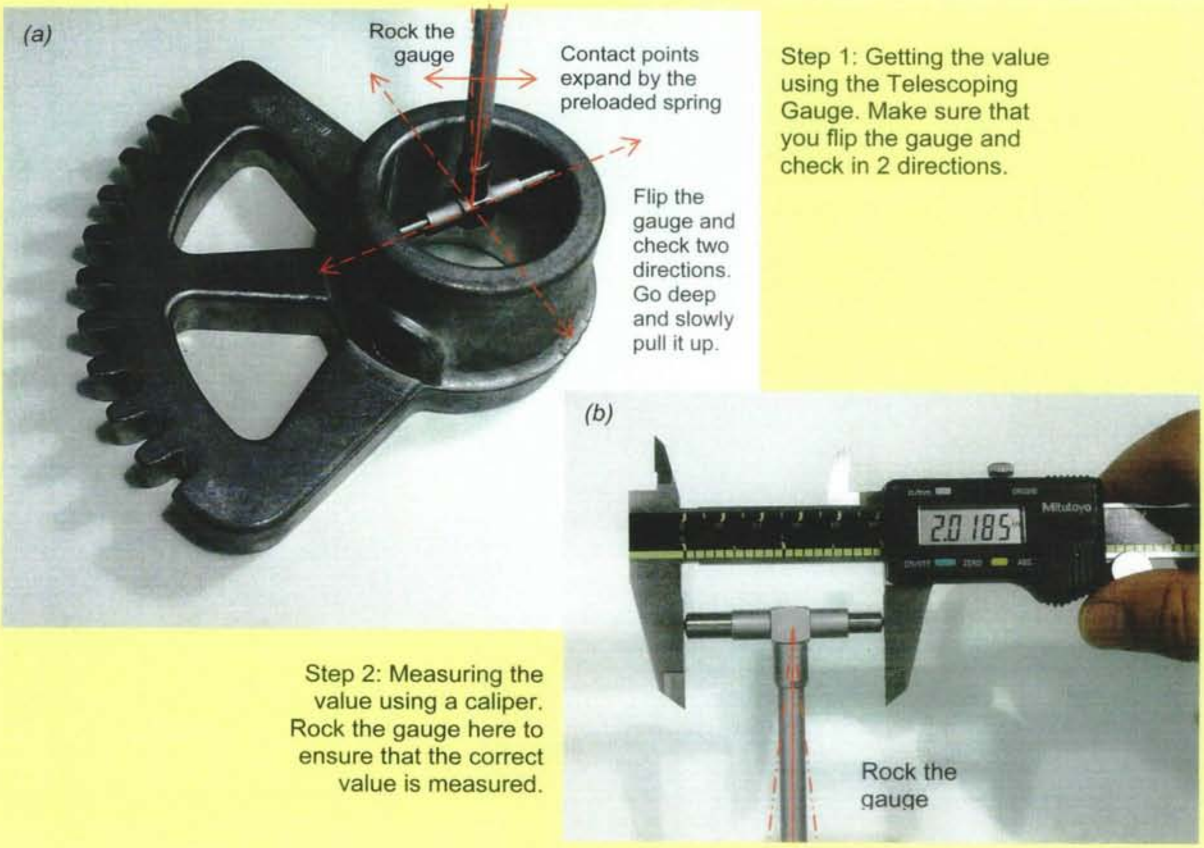
Judgment to "reject" or "accept" is subjective in Go/No-Go gauges. The gap between USL and LSL must be large enough. 50 μm (.002 in) or more is suggested for most workpieces.

It is unfortunate to see the true value of Go/No-Go gauges is underestimated by many. True, none of them produce any number, and only judge either Go or No-Go. Providing the upper and lower size limits for an application are large enough, the Go/No-Go gauge works well within certain limitations. One such limitation is that the size tolerance must be large enough to be checked by hand.

Not every part is specified with tight tolerances. Some parts for automotive components are allowed to vary within ± 0.5 mm. If the tolerance gap can be detected by a finger (50 μm or .002 in) this method will work, although sizes smaller than that may not be so apparent.

The bottom anvil for this type of caliper is always fixed and flat, while the top anvils are adjustable. Some companies use wax over the screws after initial setting to prevent tampering. This caliper is featured with a massive C-shaped frame so that the opening of the frame where parts will be inserted stays solid. It is best to use cylindrical masters if parts are also cylindrical.

Telescoping Gauge



Step 1: Getting the value using the Telescoping Gauge. Make sure that you flip the gauge and check in 2 directions.

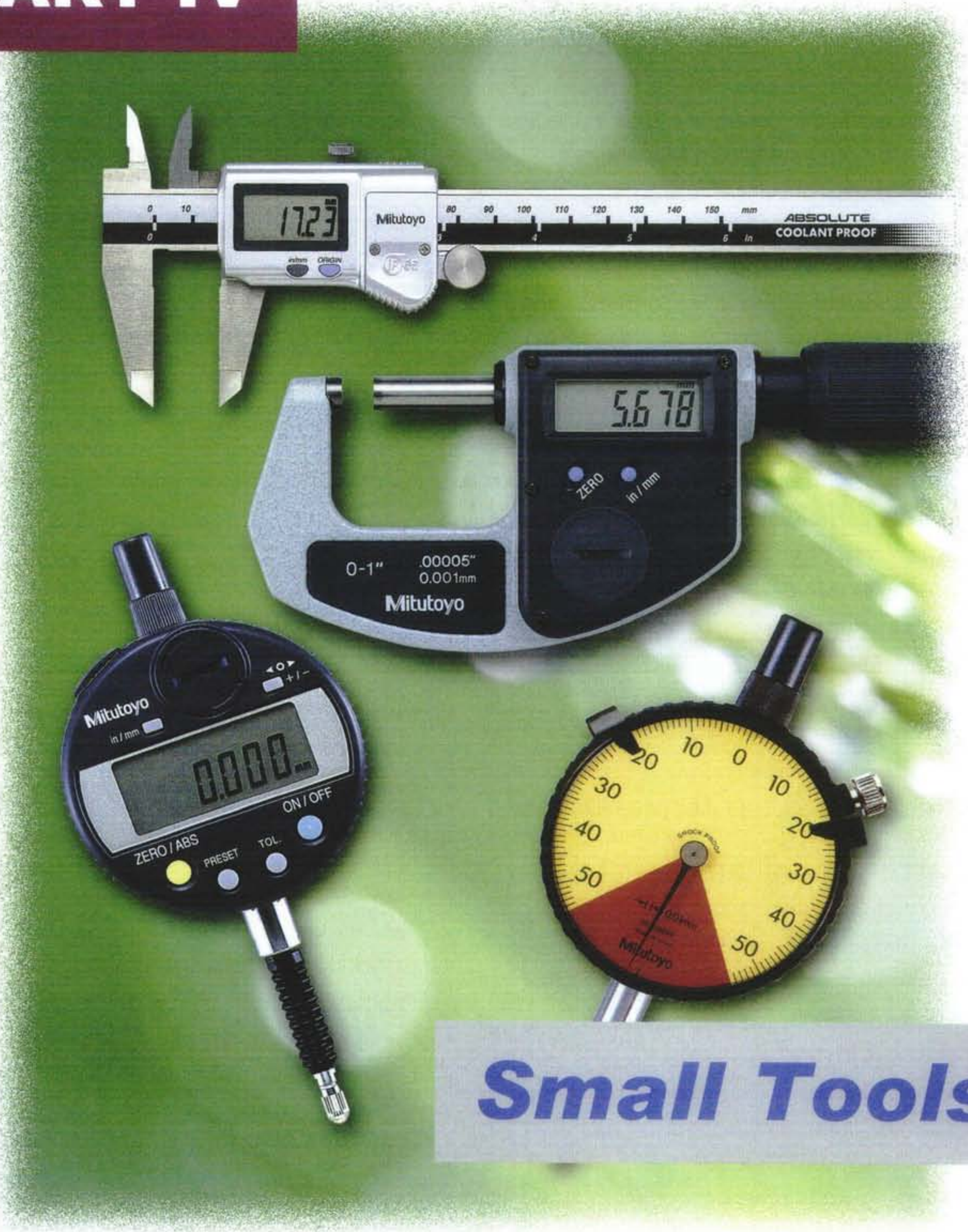
Step 2: Measuring the value using a caliper. Rock the gauge here to ensure that the correct value is measured.

Telescoping gauges are inexpensive and fully adjustable plug gauges. The advantage of having a set of telescoping gauges is clear: it may not be necessary to have a large number of plug gauges. The disadvantage is that telescoping gauges cannot replace attributes of the plug gauges. Using telescoping gauges for checking bore sizes to the resolution of 50 μm (.002 in) may be acceptable but if the tolerance gets much tighter, more accurate gauges must be employed. Plug gauges can check the function of a bore, Go or No-Go.

In spite of that, telescoping gauges are useful gauges and can quickly find inside diameters, slot openings, etc. Rock the gauge and make sure both ends are in contact with the wall surface. Clamp the gauge and bring it out so that the diameter can be measured by a caliper, a micrometer, or compared to a ring gauge. Expand the telescoping gauge in a bore and measure at least two directions. Go up and down along the wall and clamp it. Remember, this is a two-step measuring method. The first step is using the telescoping gauge to get the value *(a)*, and the second step is the measurement of that value *(b)*.

PART IV

Small Tools



PART IV:
SMALL TOOLS

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- The Birth of the Modern Micrometer
- The Parts of a Typical Micrometer
- Early Stages of Micrometer Development
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- The "4 to 1" Rule
- The 5 Point Calibration Method
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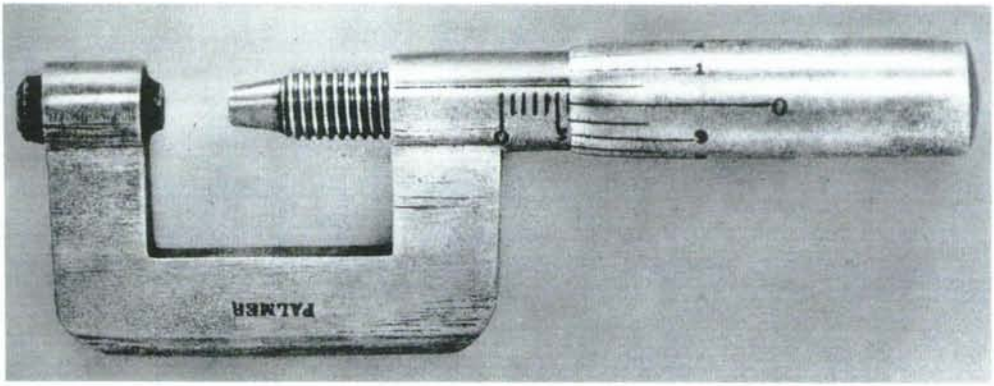
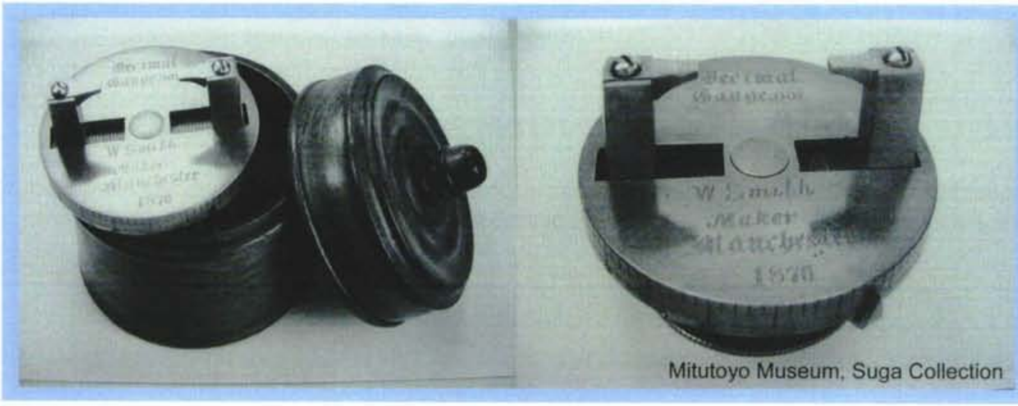
Chapter 10 Micrometers

"A WORKHORSE OF THE INDUSTRY"



The inventor of the modern micrometer, Jean Laurent Palmer, introduced the basic principles of magnification based on screw threads, a concept which is still utilised today. His design was so advanced that virtually nothing has been added to or subtracted from his original design since then.

The invention below made of brass and engraved as "Decimal Gauge .001" was, perhaps, a misguided attempt to provide one thousandth of an inch. While this was being produced in England, it was across the ocean in New England where the advancements of the micrometer took place in earnest. Among the most significant contributors in this regard are, the two distinguished gentlemen who introduced the first micrometer to the New World: Messrs. J. R. Brown and Lucian Sharpe. During their visit to the Paris Exposition in 1867, they witnessed Palmer's micrometer and recognised its potential immediately. The first model produced by them was surprisingly tiny by today's standards, but it was the birth of a new product which was to become a basic tool for all machinists.



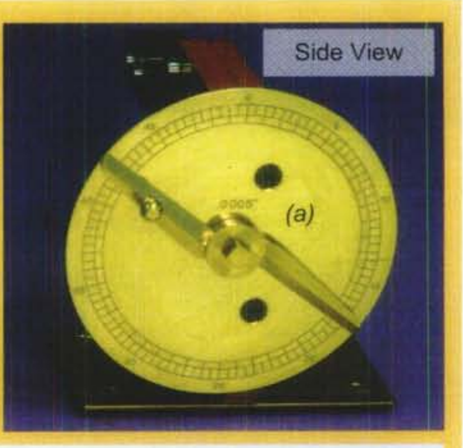
Mitutoyo Museum, Suga Collection

The smallest graduation by this invention is .001 inch. This was the third micrometer made by the inventor W. Smith of Manchester in 1876.

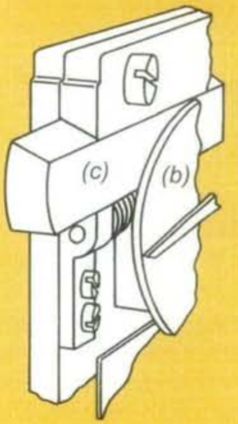
The First Micrometer

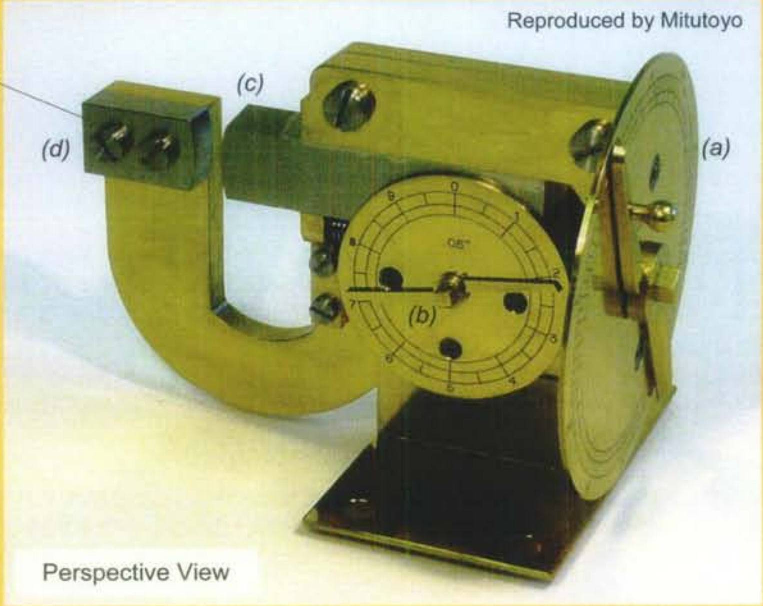
James Watt's micrometer, the first one ever produced, was rather optimistic in its graduation. The large dial *(a)*, which is analogous to the thimble in the modern micrometer, was divided into 100 equal parts of .0005 inch each. When the dial was rotated once, the threads pushed the measuring bar *(c)* .050 inch forwards, and advanced smaller dial *(b)* by 1 graduation.

He must have used this gauge many times to measure variations in engine plate thickness. The rounded anvil *(d)* and measuring bar *(c)* featured a radius, which allowed him to check concaves and other irregularities of the plates.



The anvil is adjustable for fine-tuning zero point, a standard feature even in this early part of the 20th century.



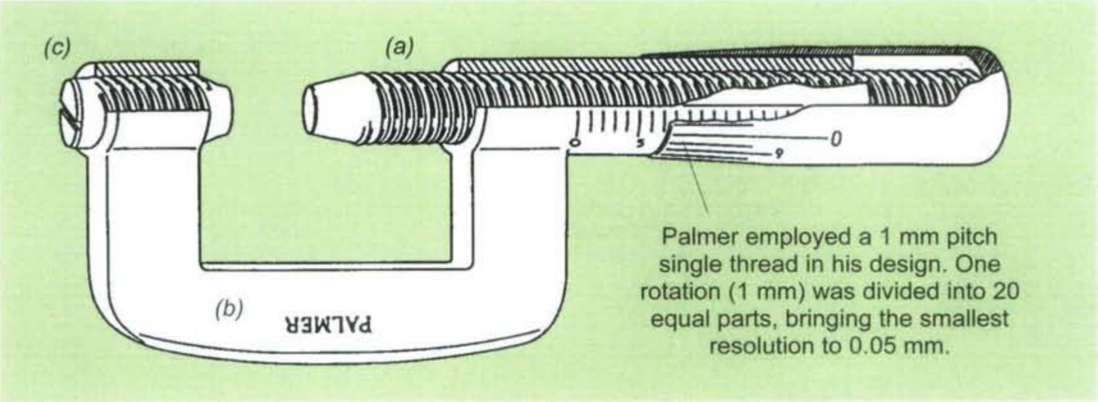


Reproduced by Mitutoyo

In 1774, John Wilkinson developed a boring machine which improved the accuracy of inside diameters. By this time, James Watt (1736-1819) might have already invented this gauge to check variations in engine cylinders' wall thickness. The inside diameter was thus simple to measure even though Watt's steam engine was 72 inches in diameter. The boring was accurate for its time, for the inside diameter was noted as having a variance of "a thin sixpence at the worst part".

Whether he measured it in fractions (i.e. 1/128) or in decimal is unknown, although the resolution of this particular model was .0005 inch *(a)*. The exact number produced is unknown; however several units could have been made. Watt's micrometer was a bench type, in contrast to Palmer's micrometer invented more than seventy years later in France (facing page). Palmer's was a hand-held micrometer capable of reading 0.05mm, and the origin of the modern micrometer. James Watt was a forerunner.

The Birth of the Modern Micrometer

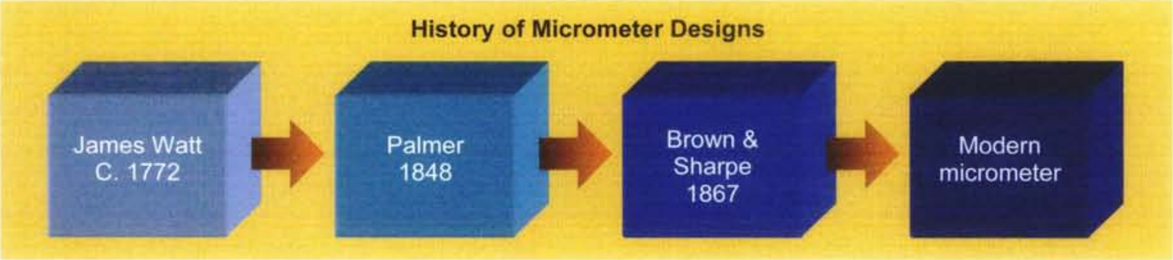


Palmer employed a 1 mm pitch single thread in his design. One rotation (1 mm) was divided into 20 equal parts, bringing the smallest resolution to 0.05 mm.

The first micrometer was invented by James Watt around 1772 was a bench-type model, and was somewhat cumbersome to operate. Unlike Palmer's it was not to be operated in one hand; a work-bench was necessary. The range was nonetheless wide enough for his steam engines, and the screw rotated by the disc-shaped thimble covered zero to one inch. It is in the micrometer of James Watt, produced in the eighteenth century, that the origin of the micrometer is traced.

The modern micrometer was invented by Palmer of France in 1848, as shown on page 131. His advanced design was based on a 1 mm single pitch open screw thread *(a)*. His compact design was the origin of the current generation of micrometers. Palmer's original design was in fact so complete that no one since then added to or removed anything from his design in terms of the principles of operation.

History of Micrometer Designs

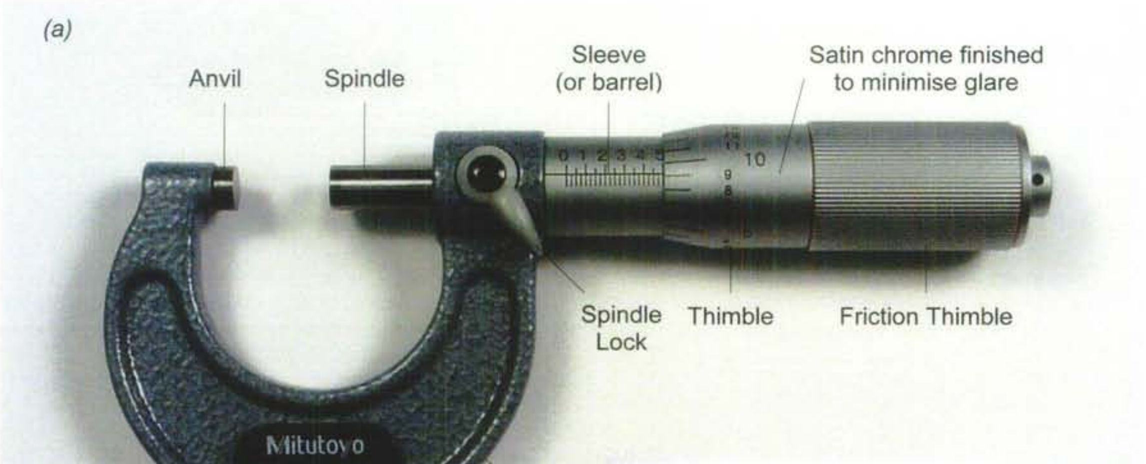


As with today's modern micrometer, Palmer's features a C-frame *(b)* and could measure and read on the same shared axis. This design turned out to be a perfect embodiment of "Abbe's Law".

After witnessing Palmer's design in Paris, Messrs. Brown and Sharpe started to improve upon the original micrometer. They chose a fine 40 threads-per-inch (TPI) spindle thread, with .025 in pitch, allowing their micrometers to have a higher resolution. By choosing 40 TPI and engraving 25 lines on the thimble, their tiny micrometer could discriminate a thickness of one thousandth of an inch (.001 in).

Palmer's anvil adjustment *(c)* for resetting the zero point was direct and straightforward as the above drawing suggests. This simple correction technique was carried over for many years, until the zero adjustment was moved from the anvil and transplanted into an adjustable graduated sleeve.

The Parts of a Typical Micrometer



Ever since the modern micrometer was invented by Palmer of France, this hand-held measuring gauge has been the workhorse of the metalworking trade. Unlike the other popular instrument, the caliper, the outside micrometer only measures 0-25 mm (0-1 in). This range was even smaller in the first Brown and Sharpe micrometer introduced for measuring brass plate thickness in 1867. Within this limitation, the micrometer provided a level of accuracy unmatched by any other gauge in the early days before the turn of the last century. The key of this enduring product life cycle is in the simplicity of screw threads.

The micrometer's unique configuration, allows users to measure and read on the same spindle axis, obeying Abbe's Law (see page 60). Here is a list of elements that compose a micrometer:

Anvil: Measurement starts from this surface. It is flat and parallel to the spindle surface and must be kept clean. While in storage, the spindle and anvil should be separated slightly.

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Spindle: Two types of spindles are used: The rotating spindle which is standard and the non-rotating spindle. Non-rotating spindles are used in Blade Micrometers, specially designed to measure narrow slots. Spindle diameter is Ø6.35 mm (.250 in) or smaller, while large micrometers are featured with larger diameter spindles (e.g. Ø8 mm).

Friction Thimble or Ratchet Stop: The first noteworthy improvement was to control the pressure at a constant level. This feature was introduced early as evident in the example *(c)* where the spindle diameter is still extremely small.

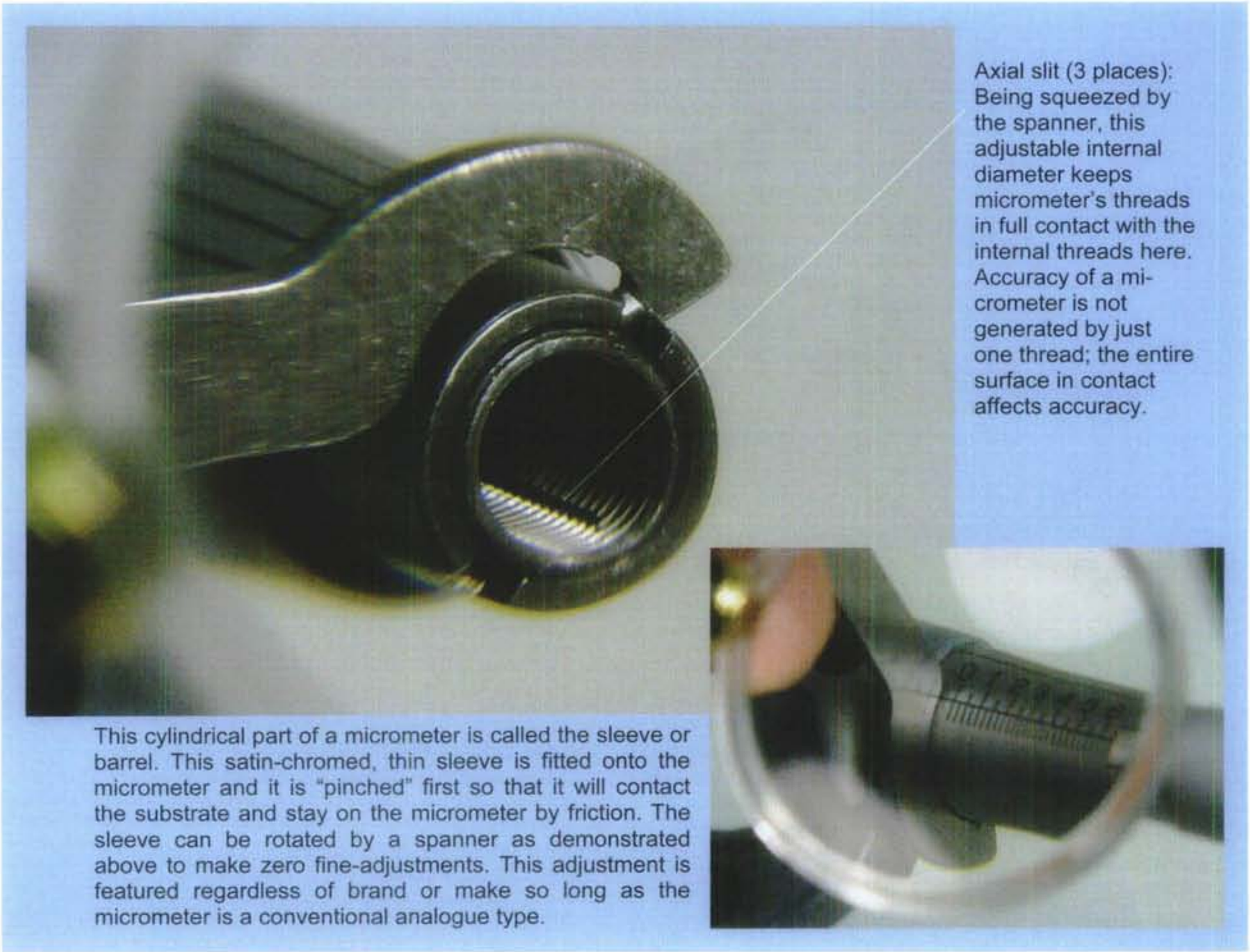
When the spindle is reinserted into the micrometer, it will return to measuring the correct dimensions as if nothing had happened. Mechanical micrometers such as this are robust measuring instruments.

If this 0-1 inch model were a digital micrometer, disassembly such as this example cannot be done, because the digital version is featured with a pin that makes it impossible to disassemble. This operation of adjusting the "feel" of a micrometer is limited to mechanical type only. There are many machinists who still use and even prefer the basic mechanical micrometer such as this model. Traditional style micrometers are just as good as the latest digital micrometers. Both offer the same accuracy because they use the same threads. One advantage for digital models is obvious: inch/metric dual reading. In addition to that, data measured may be stored electronically and then up or down loaded to other systems.

A spring wire wrapped around the shaft and making contact with the internal wall allows excessive force to be dissipated, and thus allows a constant pressure to be applied.

Mechanical micrometers are less expensive, more durable, have fewer parts to go wrong and normally last for a generation or two. If inch/metric dual reading is not a concern, then the mechanical micrometer may well be the answer for many machinists.

Micrometers are hand-held precision instruments, meaning that the accuracy produced depends on the operator's skill level. Some prefer a slightly lighter feel while turning the micrometer thimble. This may be achieved by rotating the taper nut *(a)* with a supplied spanner *(b)*. Some machinists prefer the spindle with a little more drag: turning the taper nut can also be adjusted to provide a heavier feel. Note that digital micrometers cannot be adjusted in this way.



Axial slit (3 places): Being squeezed by the spanner, this adjustable internal diameter keeps micrometer's threads in full contact with the internal threads here. Accuracy of a micrometer is not generated by just one thread; the entire surface in contact affects accuracy.

This cylindrical part of a micrometer is called the sleeve or barrel. This satin-chromed, thin sleeve is fitted onto the micrometer and it is "pinched" first so that it will contact the substrate and stay on the micrometer by friction. The sleeve can be rotated by a spanner as demonstrated above to make zero fine-adjustments. This adjustment is featured regardless of brand or make so long as the micrometer is a conventional analogue type.

Early Stages of Micrometer Development

The feature to wrap around and squeeze the spindle threads must have been patentable. When exactly this was incorporated in the micrometer is unknown. The original inventor, Palmer, did not consider the wear associated with screw threads, but the feature to take up the slack appeared before the turn of the last century as shown in the inset. The list of patents granted in the year 1909 alone indicates the heightened degree of innovations in the micrometer.

A spiral spring fitted around the spindle helped increase thread contact and minimised axial play for this ingenious Slocomb micrometer. This was patented in as early as 1897.

List of US Patents for Micrometers (Year 1909 only)

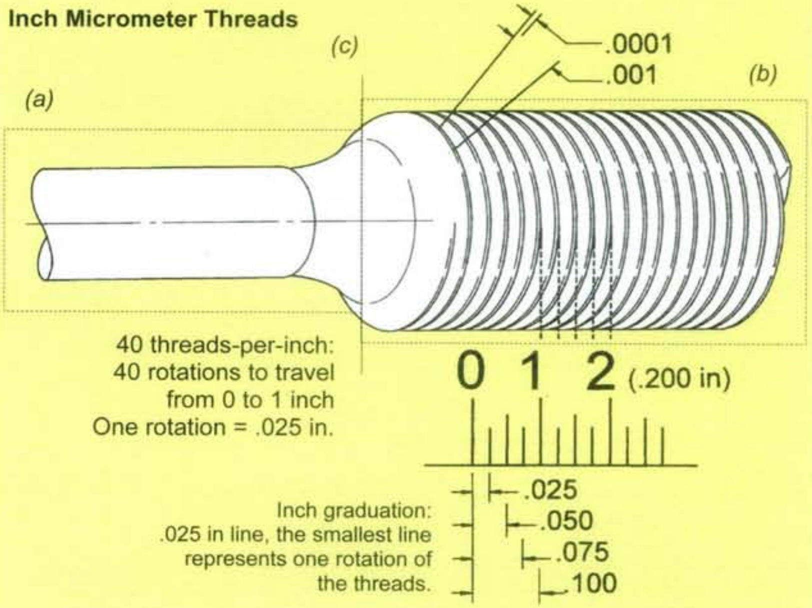
Patent Assignee	Patent No.	Date
L. Mastrangel	914,855	9th March
C. R. Pietcsh	919,455	27th April
C. O. Schellenbach	923,446	1st June
L. S. Starrett	928,889	20th July
H. S. Plant	934,692	21st Sept
F. O. Jaques	934,730	21st Sept
J. W. Whalberg	937,602	9th Oct

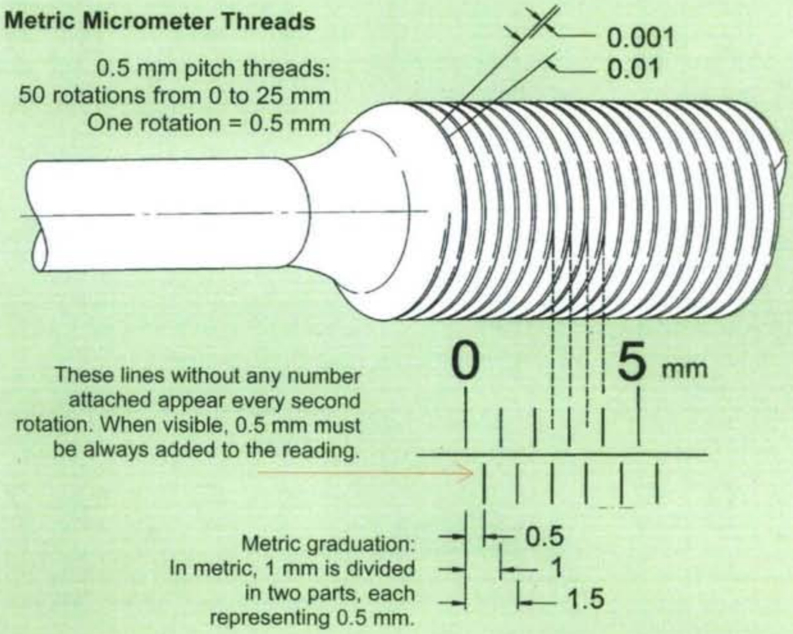
Micrometer Threads

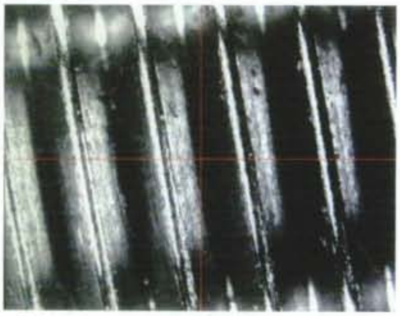
The accuracy of a micrometer is defined by its spindle threads, as shown here in these two examples. Spindle threads cannot function by themselves; they need to be kept in contact with internal threads. In any micrometer, this mechanism of internal and external threads remains hidden from the user throughout the micrometers' life unless it is intentionally disassembled.

Internal and stationary threads wrap around the spindle threads as they move forwards and backwards. The hardened and ground spindle threads usually last for the lifetime of a micrometer. It is only when foreign objects are inadvertently caught and dragged inside that the spindle must be disassembled.

In the years prior to WWII, the spindle *(a)* and threads *(b)* were made of two different materials and connected in the middle *(c)*. The advent of the carbide tip eliminated this and now threads are hardened and ground.







Micrometer spindle threads magnified at 64X by Quick Vision system using the "extra-deep focal depth" feature.

How to Read a Metric Micrometer

(1) 15.5 + 0.22 = 15.72

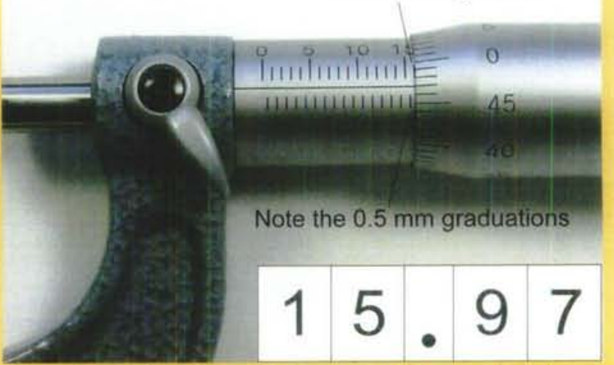
(2) 17 + 0.41 = 17.41

(3) 17.5 + 0 = 17.50

(4) 16.5 + 0.32 = 16.82

(5) 14.5 + 0.45 = 14.95

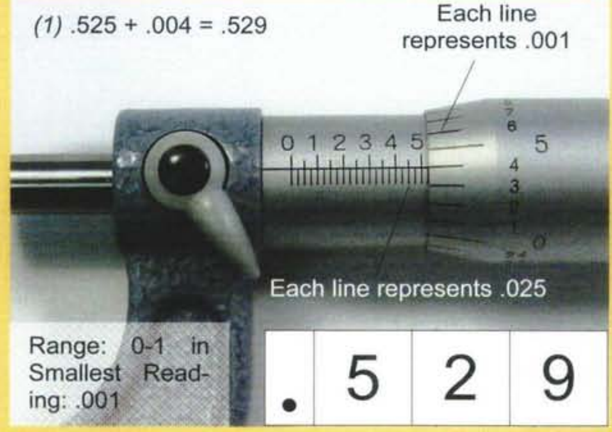
(6) 15.5 + 0.47 = 15.97



The classic reading error is 0.5mm. One must always check the lines below the horizontal centre line that separates 1 mm from 0.5mm. Short vertical lines (24 of them) each represent 0.5 mm, but the manufacturer does not engrave the number. See the last example: 15.5 + 0.47 = 15.97

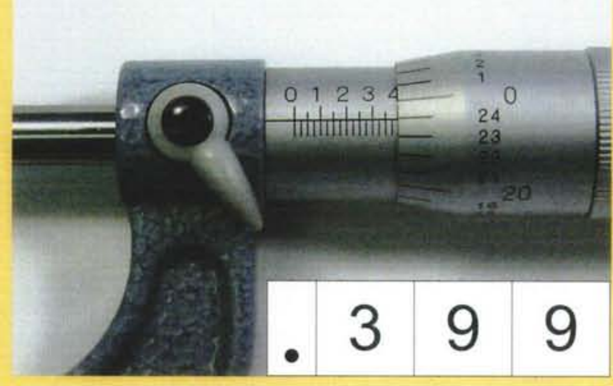
How to Read an Inch Micrometer

(1) .525 + .004 = .529

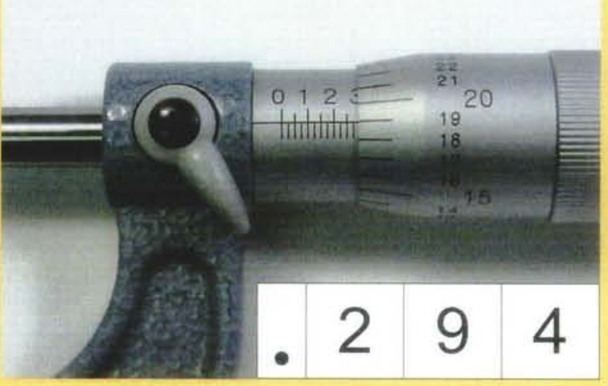


(2) .575 + .014 = .589

(3) .375 + .024 = .399



(4) .275 + .019 = .294



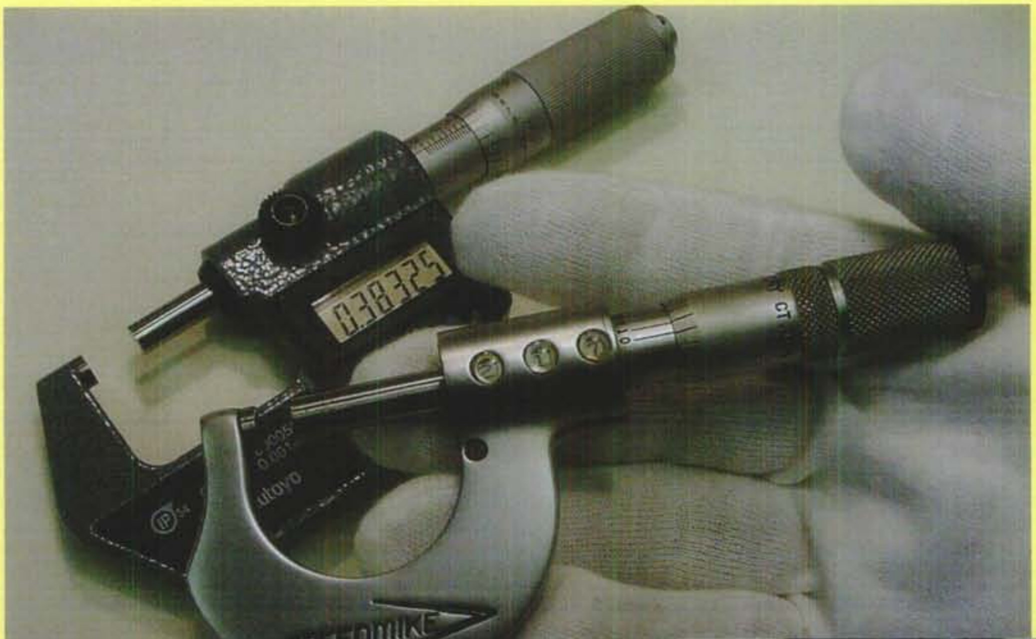
(5) .425 + .006 = .431

(6) .275 + .006 = .281

Note: The right answer to the example 3 is not .424. One way to look at it is to read .400 and subtract .001 or .400 – .001 = .399

One complete rotation of inch micrometer is .025 in and it takes 40 rotations to reach 1 inch (.025 x 40 = 1.000). The thimble is divided into 25 parts.

The Digital Micrometer



Comparing digital micrometers past and present

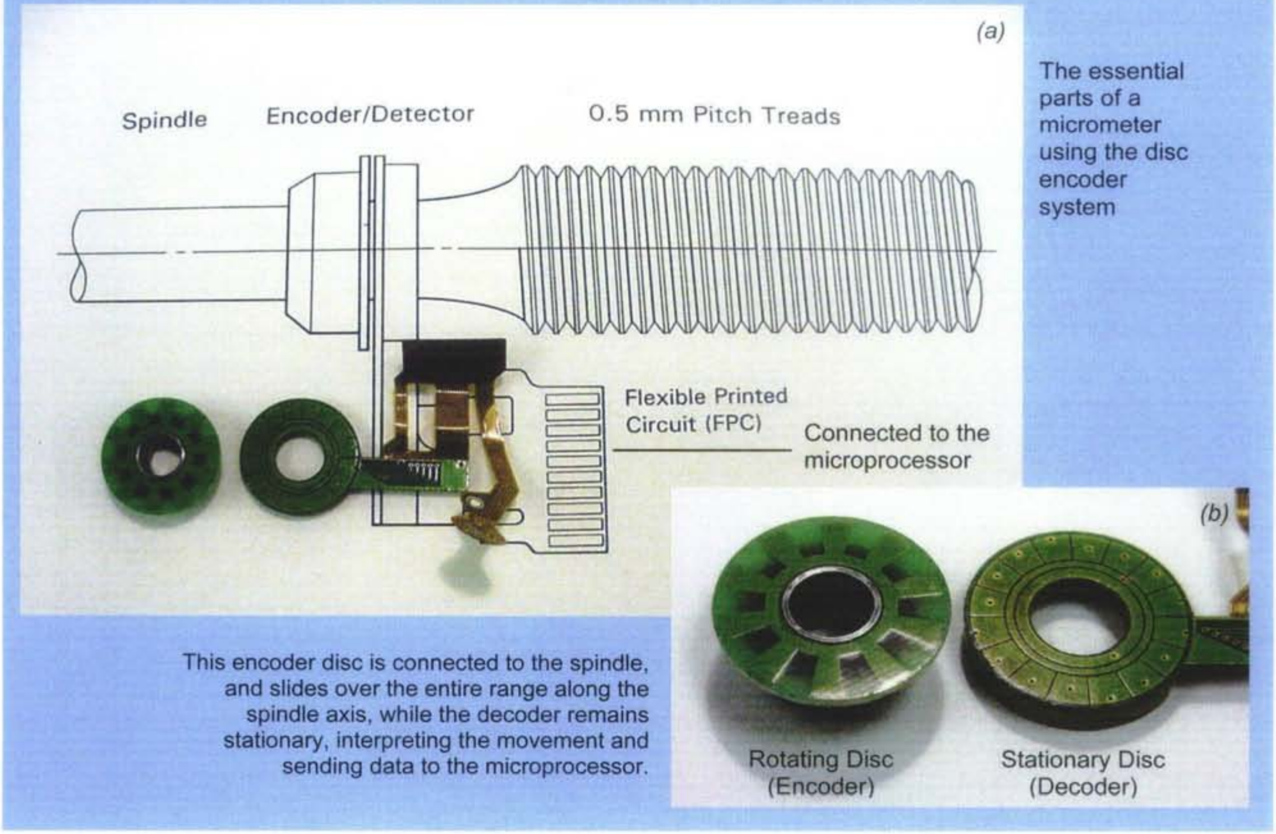
One of the major manufacturers of micrometers in the U.S. during the early days was Slocomb of Glastonbury, CT. They were among the first to produce micrometers and dominated the market during the 1920s and '30s with their innovations.

Their digital micrometer "Speedmike" was a superb example of ingenuity. It was simple in design and easy to read and use. The three digits in the windows functioned flawlessly, and the only thing it was incapable of doing was to convert between inch and metric.

The need to read a micrometer directly in digits goes back many years. One of the shortcomings of the micrometers with line graduations was the difficulty associated with reading the lines and interpreting them quickly and correctly.

Brown and Sharpe, who produced the first micrometer in the U.S., chose a 40 threads-per-inch spindle screw, where one revolution of the inch micrometer represented .025 in. As a result calculations were required to get the actual micrometer reading from the sleeve and thimble, such as 75+17=92 or 25+19=44. Even though this calculation was relatively simple, reading errors were common, especially when measurements were read quickly.

During the 1910s, the first commercially successful digital micrometer was patented and marketed by Brown & Sharpe, predating Slocomb's design shown here. Digital micrometers as we know them today came much later along with the advent of microprocessors.



The essential parts of a micrometer using the disc encoder system

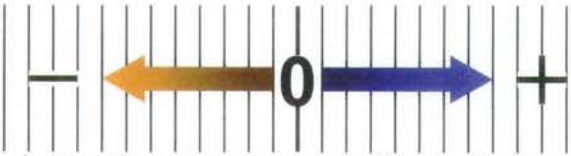
This encoder disc is connected to the spindle, and slides over the entire range along the spindle axis, while the decoder remains stationary, interpreting the movement and sending data to the microprocessor.

There are two distinctly different types of construction in digital micrometers today: one makes use of the more conventional spindle movement, and the other utilises a pair of miniature glass scales which slide over each other without rotation. This is called a linear scale micrometer, an example of which can be seen on page 158.

Of those two types, micrometers using spindle movement are more common, because this type of movement detection was designed and developed earlier. Countless types of sensors and detectors have been proposed, but in the end, as with most other inventions, the simplest method prevailed. This design features a pair of tiny disc encoders, one of which rotates together with the spindle, while the other stays stationary to count incoming signals *(b)*.

Once a measured length is captured in digits, it is only natural to have inch/metric conversion built into the microprocessor, as this feature can be appreciated in bilingual (inch/metric) nations such as the United States.

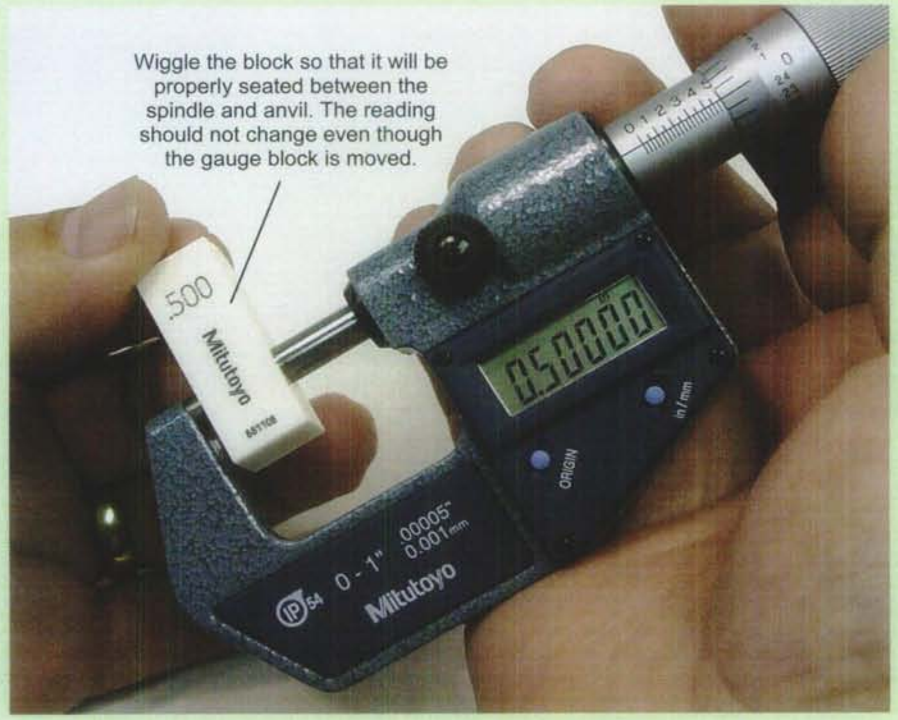
An additional benefit is that the zero point can now be set anywhere within the micrometer range. With this ability the micrometer can now be used as a "comparison" gauge where workpieces are judged whether they are below or above "zero", and by how much.



A comparison gauge measures difference from a set "zero"

In the calibration of this type of micrometer, if it is an inch/metric model only inch should be checked, since inch is derived from the metric scale.

The "4 to 1" Rule



Wiggle the block so that it will be properly seated between the spindle and anvil. The reading should not change even though the gauge block is moved.

Accuracy of a gauge block is typically: ± 50 nm (or ±.000002 in).

Accuracy of micrometer is typically: ± 2 μm (or ±.0001 in).

This ratio exceeds the 4 to 1 requirement.

The higher ratio the better it will be. "4 to 1" ratio should be the minimum requirement.

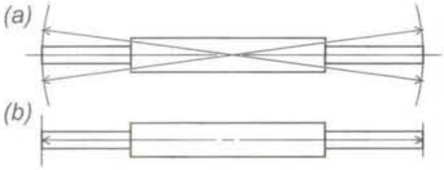
Gauge blocks, being the most accurate length standards, should always be incorporated in calibration.

"4 to 1" Rule

The old MIL-STD-45662A (now superseded by ISO-10012) states that "the collective uncertainty of the measurement standards shall not exceed 25 percent (hence 4 to 1) of the acceptable tolerance for each characteristic being calibrated".

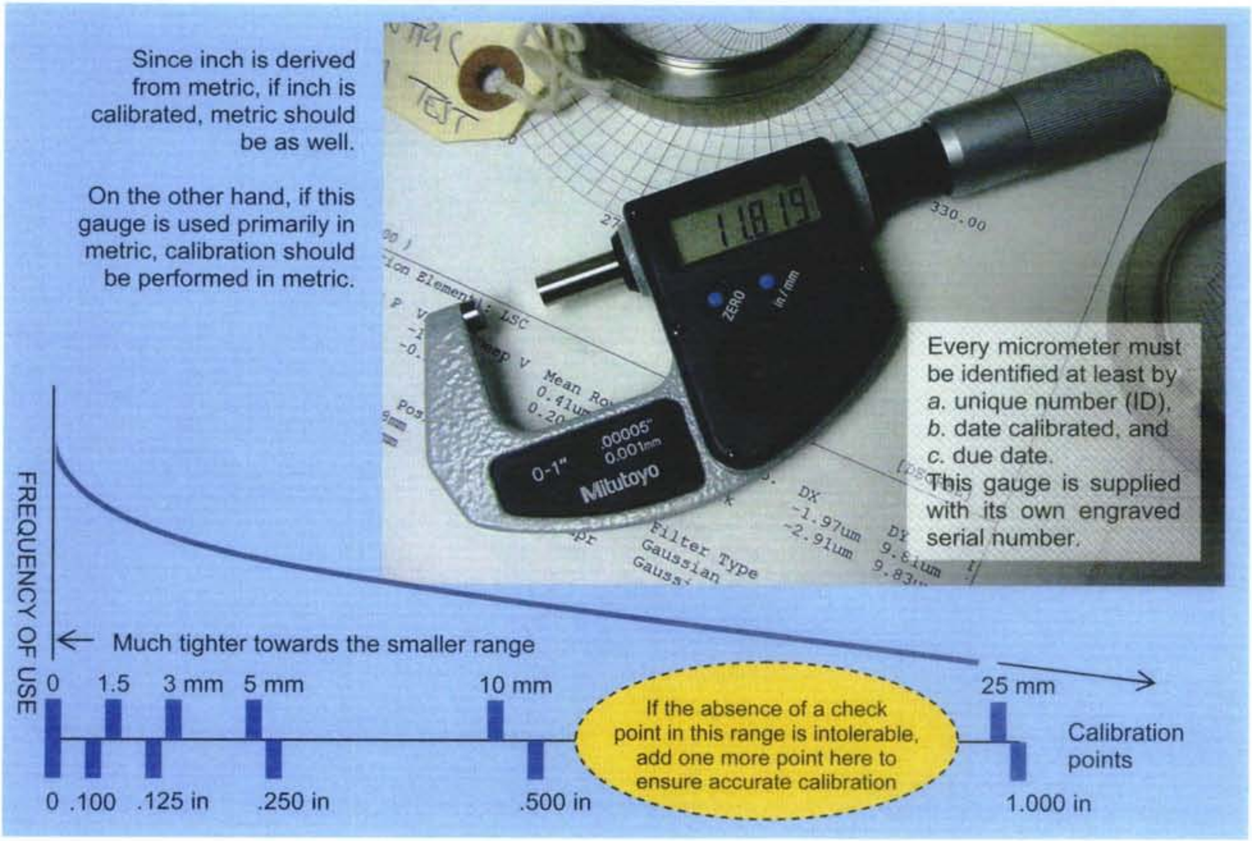
The standard used in calibrating measuring gauges must possess accuracy greater than a 4 to 1 ratio over the accuracy of a gauge being calibrated. This common rule of thumb originated some forty years ago from MIL-STD-45662A (first published in 1960). In the above demonstration, the "Unknown" gauge is the micrometer and "Known" standard is the gauge block being used. For this to be truly accurate, the gauge block must have a certificate of traceability to NIST.

The use of gauge blocks is always recommended, since no other standards are more accurate than the gauge blocks, and they are the highest in the hierarchy of precision. This way the "4 to 1 Rule" is maintained and sometimes exceeded up to 100 to 1, depending on the gauge being calibrated.



There is a dedicated standard for large micrometers called the "standard bar", Often, the bar is supplied with large-size micrometers, and its ends are either spherical *(a)* or flat *(b) (b')*. It is suggested that an uncertified bar be compared against a traceable gauge block or immediately compared against a traceable gauge block. This can be done easily on a granite surface plate.

The 5 Point Calibration Method



Since inch is derived from metric, if inch is calibrated, metric should be as well.

On the other hand, if this gauge is used primarily in metric, calibration should be performed in metric.

Every micrometer must be identified at least by *a.* unique number (ID), *b.* date calibrated, and *c.* due date. This gauge is supplied with its own engraved serial number.

If the absence of a check point in this range is intolerable, add one more point here to ensure accurate calibration

Step 1: Look at the frame for signs of damage (e.g. signs of being dropped on the floor).

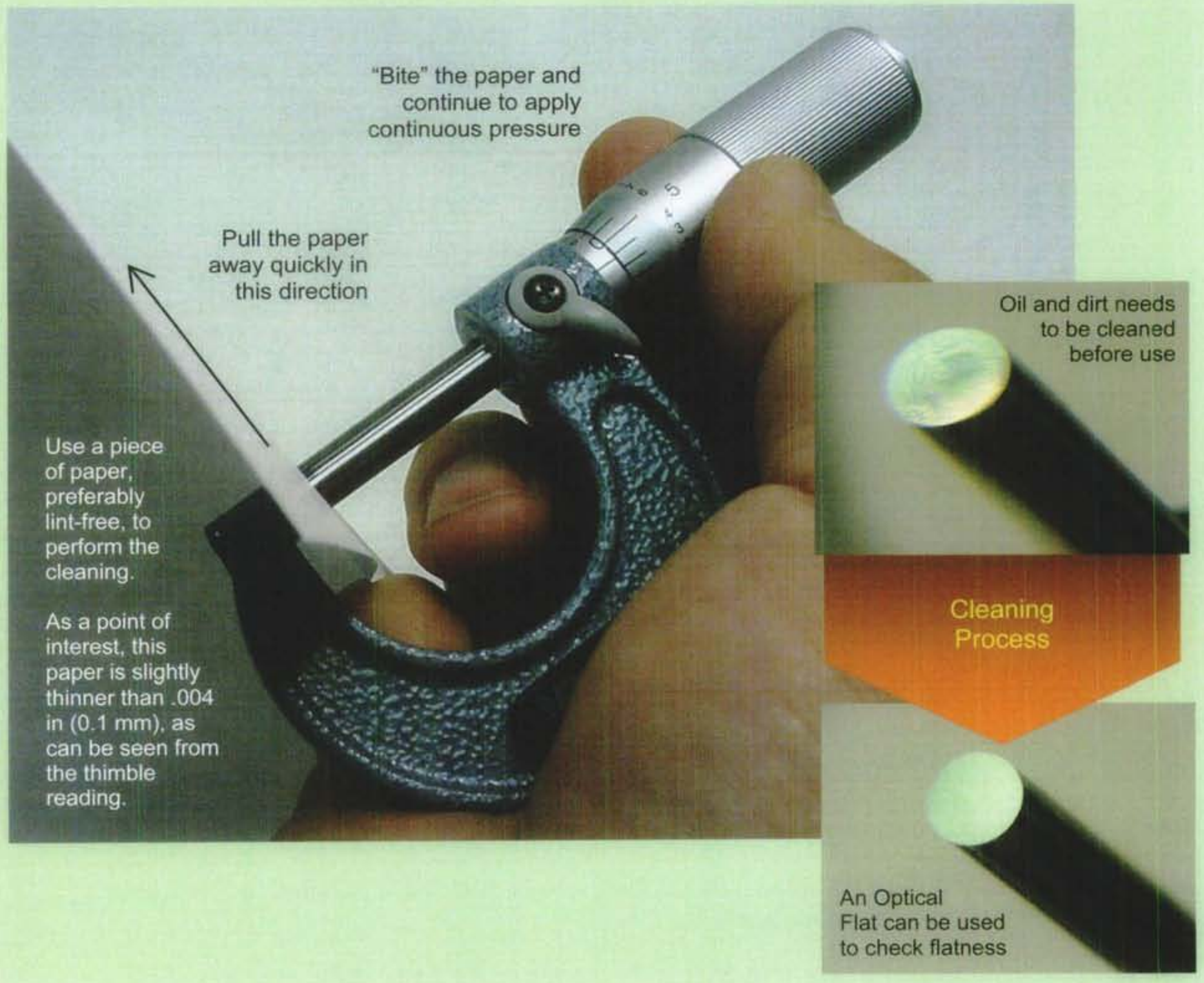
Step 2: Observe both the spindle and anvil faces. They must be flat, free of pinholes, and be clean. Frosted surfaces may indicate wear.

Step 3: Move the micrometer from 0 to 25 mm (0 to 1 in) or the entire range and check if the spindle feels continuously smooth throughout. It should not bind or freeze during the check. A hard to turn spindle is a sign of age or damage. Never use excessive force to rotate the thimble, instead have a technician look into the cause of the malfunction. If the micrometer needs repair, it must be done first. Calibration may only proceed when it is in good working order.

Step 4: Check 5 points with traceable gauge blocks: in inch micrometers 1.000, .500, .250, .125, and .0625 must be checked. The zero point should be repeatedly checked but never reported. The check points presented here are only suggestions: take the entire range, split it in half, split it in half, split it in half again, and split it for the last time. The points checked may be even better if they are replaced by .997, .502, .246, .128, .611 or any other number for that matter.

Step 5: If a specific value is checked on a regular basis, by all means include that number in the calibration procedure to safeguard the system.

How to Clean Micrometer Faces



Use a piece of paper, preferably lint-free, to perform the cleaning.

As a point of interest, this paper is slightly thinner than .004 in (0.1 mm), as can be seen from the thimble reading.

All micrometers must be cleaned even if they are brand new. Brand new micrometers are covered with preservatives, particularly the spindle and anvil faces. The thickness of such agents may exceed 20 to 30 μm (.0008 to .0012 in), thus they must be removed before use.

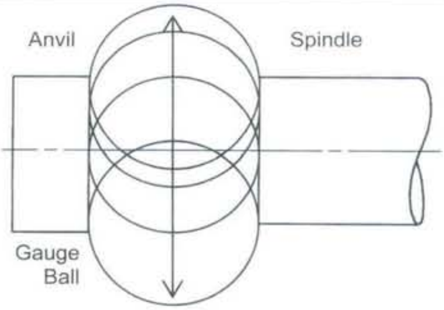
Ideally, both anvil and spindle faces must look like a clean mirror. Frosted surfaces on some old micrometers may indicate wear. Whether carbide tipped or not, the faces should always be spotless before the micrometer is used for any measuring.

The cleaning method shown above should take no more than three seconds. Using a piece of lint-free paper, "bite" the paper by bringing the spindle closer to the anvil. Continuing to apply pressure at the thimble, work the paper across the surface slowly, then quickly pull it away. Check that the anvil and spindle faces are a mirror finish, otherwise repeat the process. For digital micrometers, make sure this cleaning takes place before zero setting.

Checking Parallelism of Micrometer Faces

In the rare case where a micrometer is misused, parallelism between the anvil and spindle faces may suffer (e.g. dropped on the concrete floor or C-frame is bent). Measuring hard or rough workpieces such as grinding wheels may also cause wear over time on the micrometer faces, resulting in them becoming convex. This is obvious when a face appears frosty.

One way to detect this is to measure a gauge ball in five points, as shown at right. If all five readings are equal, it must be parallel. If the surfaces are worn out and the faces are concave, this method will detect it. The gauge block calibration method outlined on pages 142 and 143 will not. An alternative method is to use an optical parallel, shown on the next page.



Check the 3 and 9 o'clock positions as well. Ideally, parallelism should be less than 1 µm (40 µin).

Gauge balls are also supplied with a stem pierced into them for better handling.

Tags aid identification of the size and grade of the attached gauge ball.

Gauge Balls are available in a variety of sizes and grades:

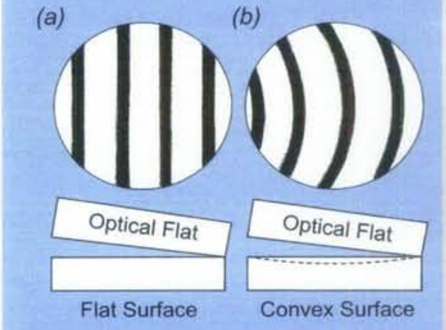
Grade	Specifications
5	Diameter Variation = 0.13 µm (5 µin)
10	Diameter Variation = 0.25 µm (10 µin)
25	Diameter Variation = 0.64 µm (25 µin)
50	Diameter Variation = 1.25 µm (50 µin)

Ball Grade 5 is limited to SØ1.5 to SØ25 mm sizes only (1/16 to 1 inch). SØ = Spherical diameter

Flatness of this Optical Flat was certified at NIST. The numbers on the chart are in nanometres. The plotted chart indicates that the flatness of this optical flat is within 10 nm. Although there are more accurate optical flats available, the level of accuracy represented above is sufficient for checking micrometer anvil and spindle flatness as well as parallelism.

The supplier may call them
(a) single-sided for optical flat, and
(b) double-sided for optical parallel.

When the optical flat is held in the arrangement at right, dark bands known as interference fringes will be visible. This pattern gives a visual clue as to how flat the surface being inspected is. A small wedge of air must be present as illustrated in the line drawings below.

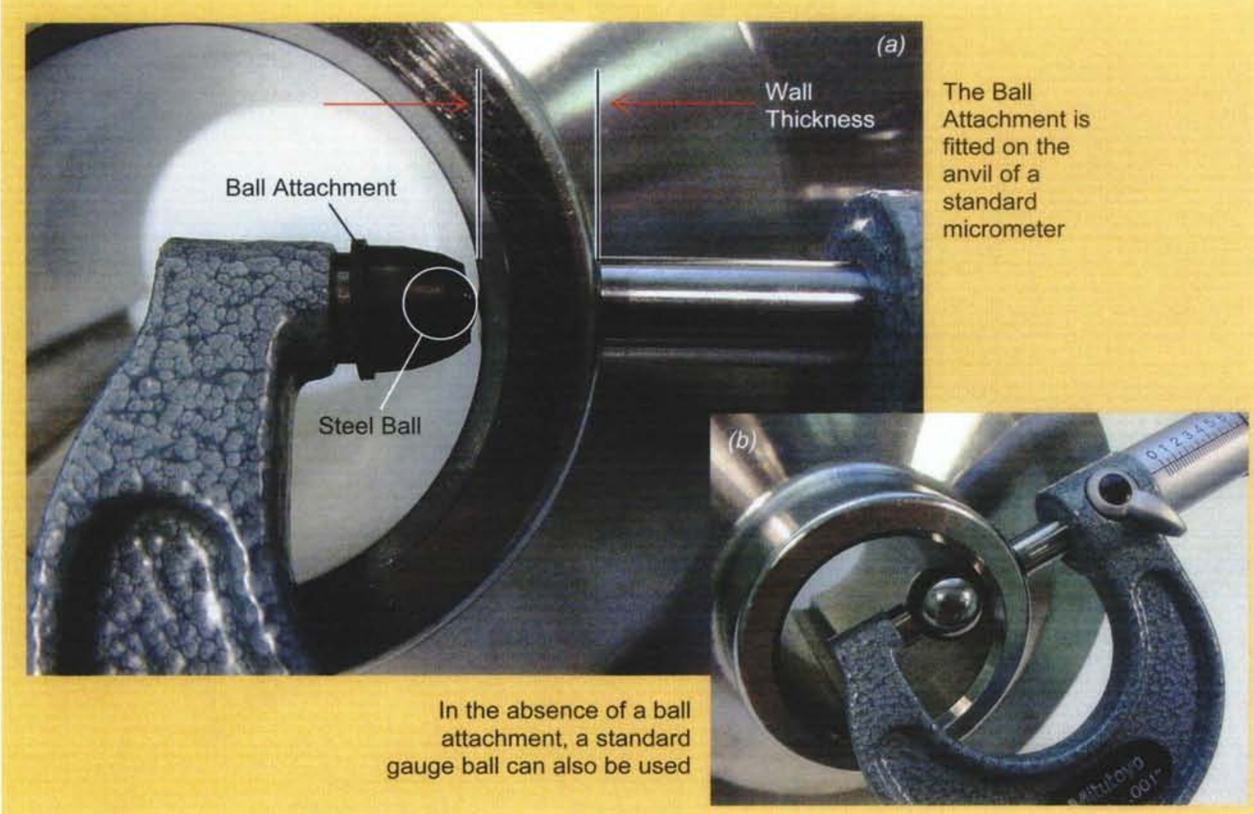


Misalignment between the anvil and spindle may be the result of accidental drops. This digital micrometer is designed to show E05 for error instead of a reading if dropped.

Most micrometers available today are featured with carbide tips on the anvil and spindle faces for longer tool life. They are made of tungsten carbide and lapped flat and parallel to each other. When new, they are mirror-clean, but after years of use the surfaces may become frosty. This condition may occur when a micrometer is subjected to measuring grinding wheels and the like. Measuring faces are normally flat and parallel within 1 μm (.000040 in).

To check flatness using an optical flat, place it against the surface to be inspected, ensuring that there is a small wedge of air present. If the interference fringes are straight and parallel *(a)*, then the surface can be considered flat, otherwise they will show up as curved bands *(b)*.

Measuring Wall Thickness



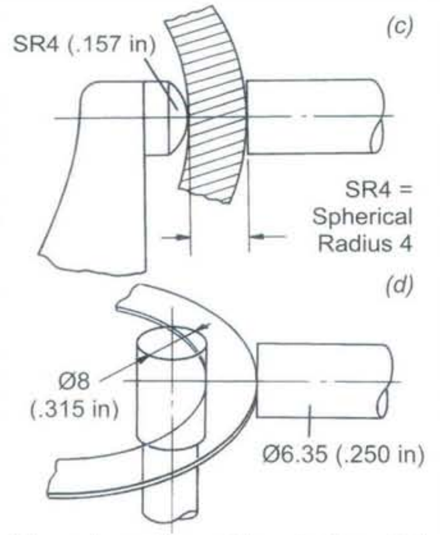
The Ball Attachment is fitted on the anvil of a standard micrometer

In the absence of a ball attachment, a standard gauge ball can also be used

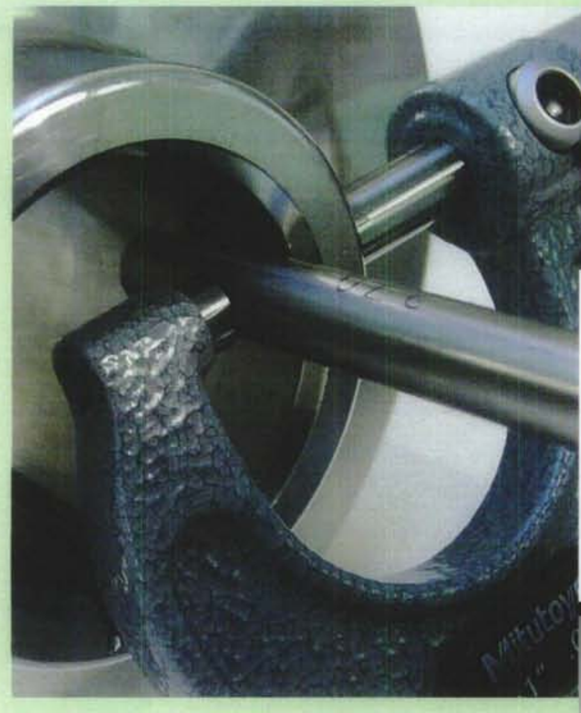
If the dimension specified is slightly curved like the examples on this page, the standard micrometer with its flat anvil and spindle faces cannot be used to measure wall thickness. Standard micrometers are good for flat and parallel features or for measuring outside diameters. They are suitable for most purposes, as most products are flat and parallel, or cylindrical, except these examples, where they will measure larger than what the dimension actually is.

As the wall is curved, a similarly curved anvil is necessary to measure wall thickness. There is a specific accessory called a "ball attachment" as shown above *(a)*, consisting of a steel ball bearing having a sphericity of approximately 0.25 µm (10 µin) or better, and a rubber boot to hold it in place against the micrometer anvil.

However, if it is unavailable, it may be substituted by any size gauge ball arranged as illustrated in *(b)*. Measure the wall thickness with the ball placed against the inner edge of the curved surface, then subtract its diameter from the final reading. Without the ball attachment, there is a risk that the ball may fall and be lost on the shop floor, which is why the accessory is recommended.



Micrometers with special anvils *(c)* and *(d)*, are made for this purpose.



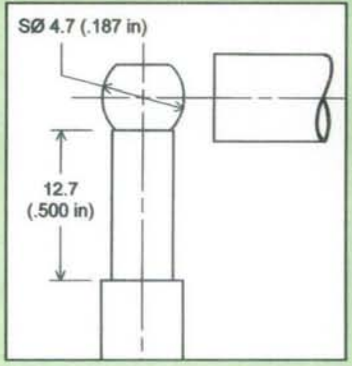
(a)

A plug gauge can be used when a ball gauge is not available

(b)

A "Unimike" with its unique clamping anvil

Having a SØ 4.7 (.187 in) ball on the anvil, this special micrometer can measure wall and tube thickness up to 25 mm (1 in). The reach is 12.7 (.500 in).



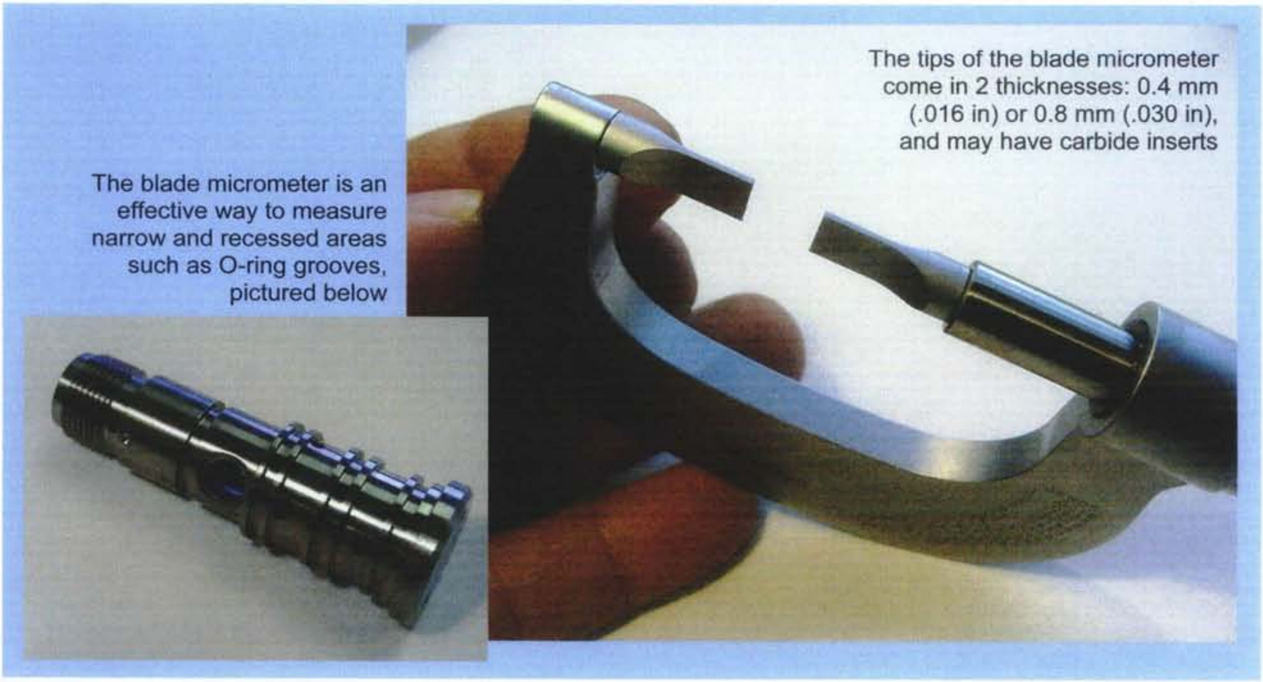
(c)

Although the ball attachment is an inexpensive and convenient accessory, if a ball (any size) is not immediately available, a plug gauge may be used instead as illustrated in *(a)*. However, measuring the wall thickness with a plug gauge is harder than measuring it with a steel ball. First, close the micrometer, zero-set and read the diameter of the plug. If minus is indicated after the size (– engraved, see page 110) the plug is usually smaller by 5 µm (.0002 in). The plug diameter must also be calibrated. As always, the diameter must be subtracted from the final reading.

When the wall thickness of a tube is too small for all of the prior methods, a plug gauge can be clamped onto a specialised micrometer known as a "Unimike" featuring a vise-like special anvil for this application *(b)*.

If measurements of cylindrical walls are done frequently, the extra step of subtracting the diameter of balls or plug gauges can be eliminated by using special purpose micrometers with ball anvils *(c)*.

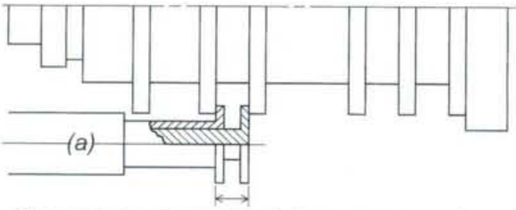
Blade Micrometers



The blade micrometer is an effective way to measure narrow and recessed areas such as O-ring grooves, pictured below

The tips of the blade micrometer come in 2 thicknesses: 0.4 mm (.016 in) or 0.8 mm (.030 in), and may have carbide inserts

Of the many special application micrometers, the blade micrometer shown here is amongst the most popular. O-ring grooves and other recessed areas are aptly known as "hard-to-get-at" places. Without a special micrometer such as this non-rotating spindle blade micrometer, it is nearly impossible to measure recessed diameters protected by flanges reliably.



The groove micrometer *(a)* can measure between flanges, such as in this example.

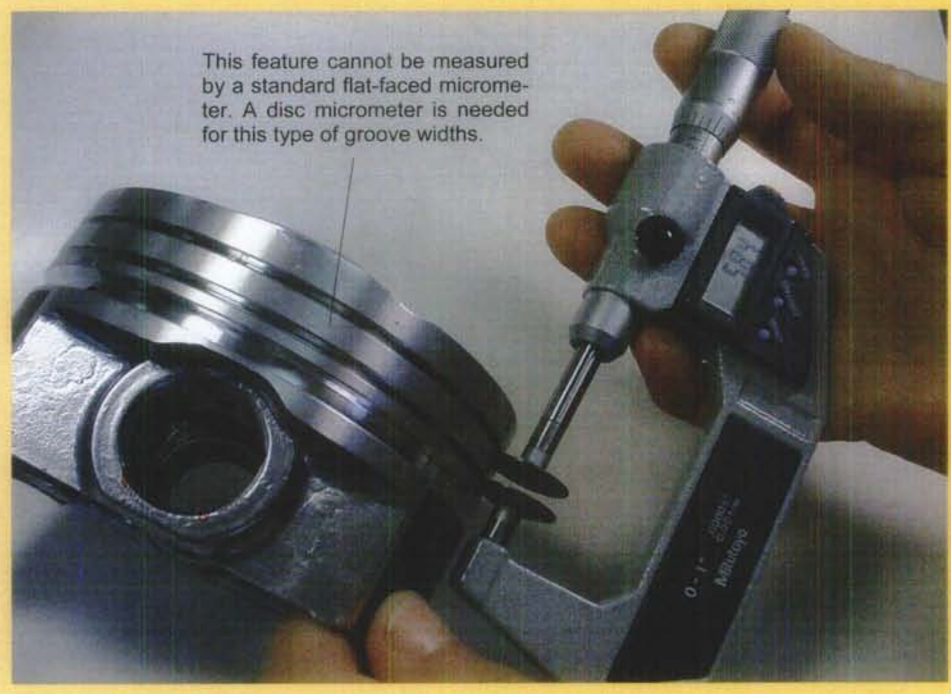
To measure the distance between them, another special micrometer called the "groove" micrometer (for groove widths) may be used. There are generally two varieties of this blade micrometer: Standard rotating-spindle types, and non-rotating spindle types, of which the non-rotating types are much easier to measure with. However, accuracy suffers a little in the non-rotating spindle configuration. ±3 μm (±.00015 in) — 50% more than the standard type micrometer — is specified.

If the opening of the O-Ring groove is featured with a chamfer at 45° with customary ±1°, the quickest answer to find this angle is to go to the Profile Projector and magnify the entire profile at 10X.

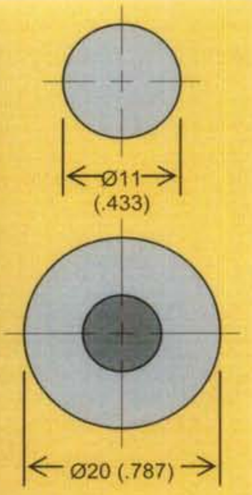
If the grooves which are extremely narrow, the thinnest blade available is 0.4 mm (.016 in). Since the surface area of this blade is minimal, it may also suffer wear faster. Blade micrometers with carbide inserts are also produced for this reason.

The largest standard blade micrometer has a 0-100 mm range. For larger sizes, Profile Projectors are generally recommended

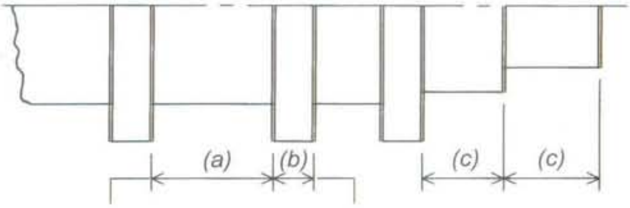
Disc Micrometers



This feature cannot be measured by a standard flat-faced micrometer. A disc micrometer is needed for this type of groove widths.

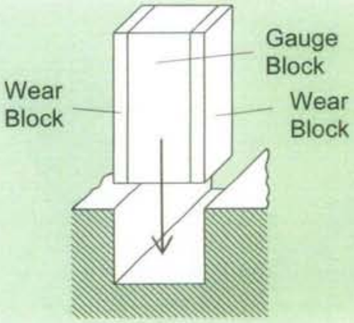


Standard disc micrometers have rotating spindles, making the disc slide away when it is critical to read. Non-rotating types are better.



- (a) Internal dimensions are best measured by a groove micrometer
- (b) Groove widths best measured with a disc micrometer
- (c) Depth micrometers best to measure step depth

Amongst the many type of specialised micrometers offered, the disc micrometer is used frequently due to the fact that the standard micrometer cannot reach certain areas. One example of this is a groove width such as the one shown above, where the only hand tool that can be used is disc micrometer. While more sophisticated measuring gauges and machines such as CMM or Optical Comparators are available, simple on the spot measuring applications on the shop floor may similarly only need simple gauges.



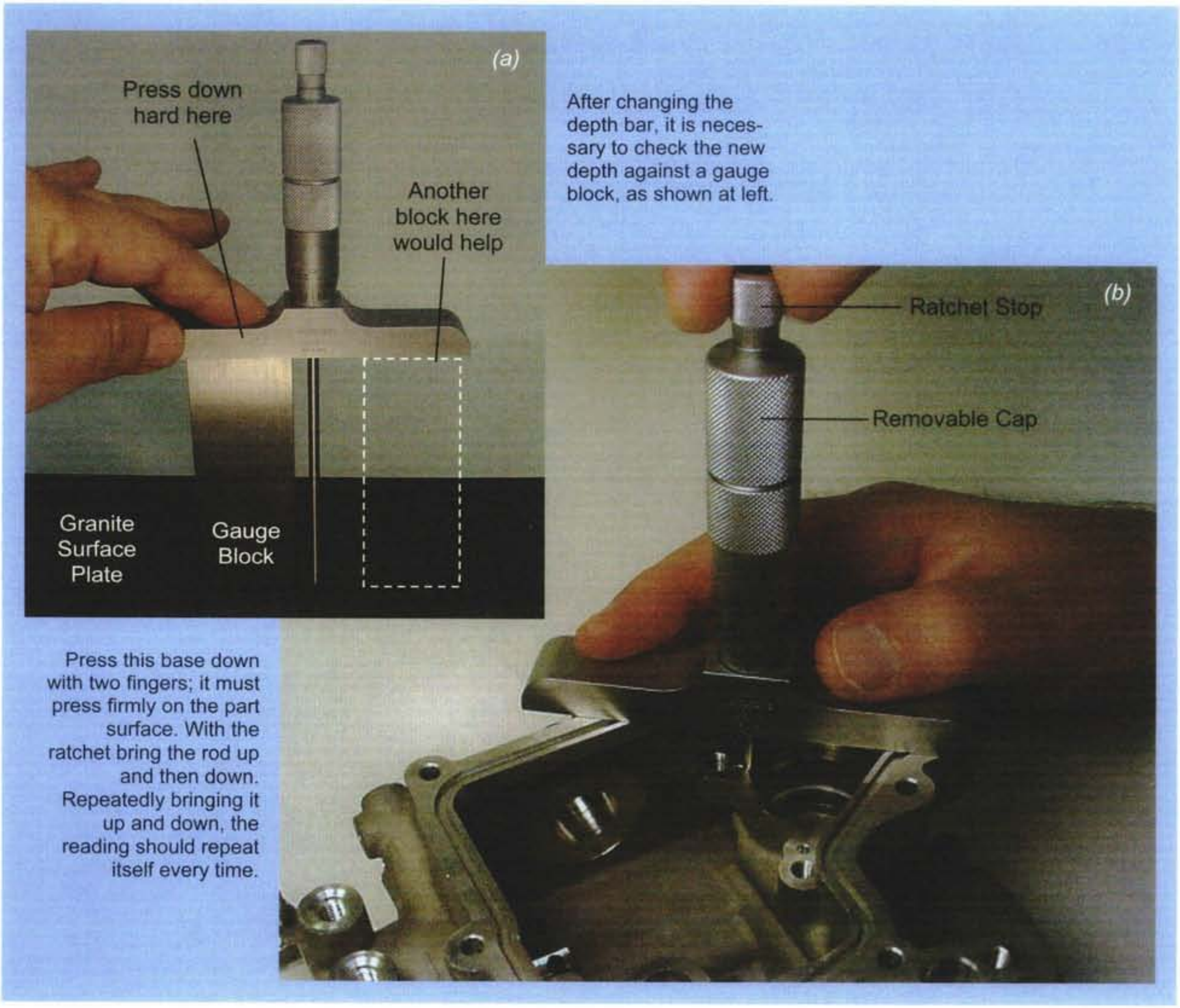
If a slot is deep enough, slot width may be checked with a pin or plug gauge. When a slot is shallow, gauge blocks flanked by a pair of "wear" blocks may be a better choice. They are usually made of carbide and come in pairs.

For very narrow slots, a feeler gauge is often used. Make sure the blade thickness is accurate by checking with a micrometer. For a slot more than 1 mm (.050 in) in width, a gauge block should be used instead.

Depth Micrometers

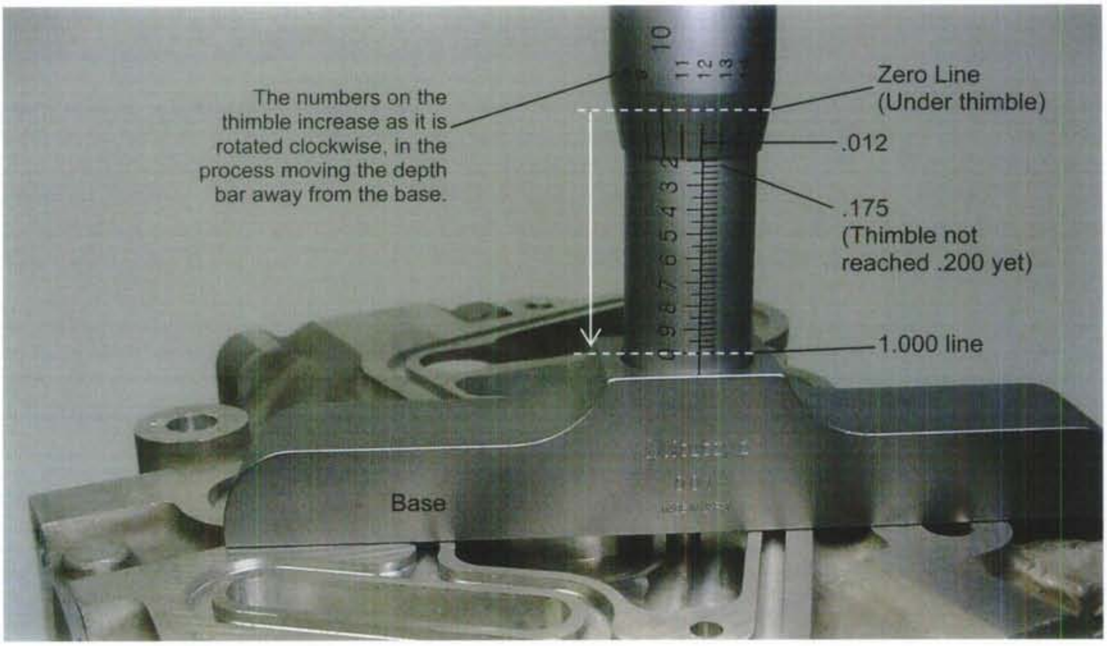
Regular outside micrometers and depth micrometers both use the same spindle and line graduations, except that the order of graduation is reversed in depth micrometers. In outside micrometers, the graduation progresses 0-1-2-3-4-5-6-7-8-9-0, but the depth micrometer reverses that to 0-9-8-7-6-5-4-3-2-1-0 on the sleeve (see the facing page). The reasons for this reversal are simple: In depth micrometers, when the depth bar is extended and moved away from the base (zero point), the reading will increase. Therefore as the length of the depth bar increases, as does the reading. As a result, line graduated depth micrometers are more difficult to read, and their digital versions more popular.

In handling the micrometer during measurement, it is important that the base must always be pressed down hard. See *(a)* and *(b)*. The ratchet stop should be used for more consistent measurements: click it three times after reaching the stopping point to ensure that consistent pressure is being exerted for each reading.



After changing the depth bar, it is necessary to check the new depth against a gauge block, as shown at left.

Press this base down with two fingers; it must press firmly on the part surface. With the ratchet bring the rod up and then down. Repeatedly bringing it up and down, the reading should repeat itself every time.



When reading the line graduated depth micrometer, it is important to remember that the only difference between the regular outside micrometers and depth micrometers is the graduations, which are reversed in depth micrometers. Reading them in inch or metric is not difficult or complicated. Taking a little more time, one must read the graduation lines carefully.

The above reading example .187 in is a little tricky to read because of the poor camera angle. The thimble has passed the .175 graduation line but not quite reached .200 line yet. The reading on the thimble is .012 in. Adding the two together, the total reading is .187 in (.175 + .012) as indicated above.

Make sure that the cap is tight while in use; a loose cap means an unsettled zero point. Also, hold the base down firmly so that it will not be raised by the descending depth bar that pushes up. At the moment of contact, back off and try again. Make sure the micrometer's base is firmly seated against the work surface.

Depth micrometers also feature interchangeable depth bars to measure various depth ranges. It can be accessed through the removable cap attached to the ratchet stop.

Always ensure that the surface of the depth bar is clean before inserting it, and check the new depth against a gauge block after each change, as shown on the previous page.

The depth bar featured at the end of the caliper shown here is not adequate for depth measurements when compared against the right tool, which is the depth micrometer.

The advantage of the depth micrometer is its flat base, usually 100 mm (4 in) or 63 mm (2.5 in) long and 16 mm (.63 in) wide. This bottom plane provides an excellent reference to start measuring from.

The bottom face of the caliper is narrow and limited, inadvertently allowing the caliper to read the depth slightly longer if the caliper is not applied perpendicularly.

Within this limitation, however, the caliper may still be used for rough estimates of depth or step.

Depth micrometers, with or without digital readings, are almost always supplied with additional interchangeable bars. Assuming that the depth bars stay straight and are checked by a gauge block whenever the bar is interchanged, the depth micrometer is capable of measuring depths as deep as 300 mm (12 in). The longer the bar, the more care will be required not to injure or twist the bar. Roll the bar on the table to observe if it is straight.

The bottom surface serves as a reference plane from where the measurement starts to increase as the end of the bar moves away from the base. To have a digital micrometer makes sense for the depth micrometer because the reading takes a little longer than usual if digital reading is not provided.

Being digital, seamless conversion between inch and metric is always available. This and other digital micrometers measure dimensions in metric first and convert them into inch equivalent. As shown below, always firmly press down the base.

Two and Three Point Gauges

Three-legged contact pins (made of carbide) are pushed against the wall, thus the gauge aligns itself with the bore axis. Operators find this gauge easier to use over the two-point bore gauges.

This is a self-aligned, three-point internal micrometer called "Holtest"

Generally, there are several ways to check inside diameters, depending on how many contact points are taken. Each method has its advantages and disadvantages:

1) Two-point measuring bore gauge
2) Three-point measuring micrometer
3) Multi-point measuring CMM
4) Plug gauge (for functional check)
5) Air gauge (non-contact)

One of the observations from the floor is that the gauge shown above repeats well. Reproducibility, also known as "appraiser-to-appraiser variance", appears to be smaller with this gauge. It is smaller because of the self-aligning nature of this gauge, which finds the inside diameter calculated from three contact points. It is easier to use and less likely to pick up incorrect measurements. However, oval diameters may not be able to be measured accurately, for which a two-point micrometer should be used. If the bore happens to be triangular, then three-point gauge can detect the three-lobe condition by rotating the gauge 60°. A multi-point input such as CMM tends to report "best-fit" circles (least square circles) unless each measured point relative to the centre is reviewed.

Inside measurements are more difficult to take than outside measurements. Ring gauges of XXX or XX grades must be used when tolerance is tight, and clearances seem tighter than expected. Bores are made to accept shafts; the fit between the two mating parts should fall into one of the three categories: (1) clearance fit, (2) transition fit, or (3) interference fit, of which the first, clearance fit, is the most common. The CMM measures inside diameters as well, but it is for general purpose. The single-purpose bore gauge of this type can take readings faster, but needs a ring gauge to be present to check the value.

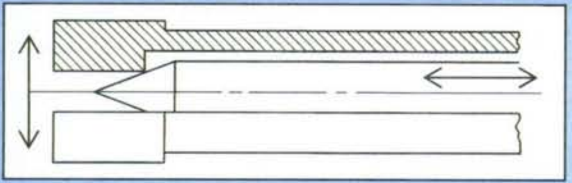
When the diameter gets smaller than 6 mm (.240 in), three-point configuration cannot be fitted into a much smaller gauge. The solution is to use the mechanically simpler two-point system. In addition to the two-point method, there is one more way to measure small holes — pin gauges. The limitation of the Go/No-go gauge is in the assessment whether it is Go or No-go is subjective: they do not reveal the actual size.

A pin or plug gauge may go smoothly into the hole but it is difficult to quantify the smoothness. With that inherent disadvantage in pin gauges, it is still recommended that pin gauges (called attribute gauges) be used alongside measuring gauges (variable gauges).

If a CMM is used instead of conventional gauges, in addition to hole diameter, its centre coordinates can be also measured. Hand-held gauges check size only, while CMM does much more.

Two Point Measuring Gauges

The sleeve is fully adjustable, but a ring gauge is needed to zero-set.

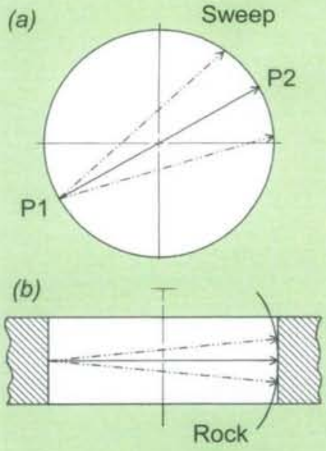


This two-point inside gauge resembles a pin gauge: the descending cone within the probe widens the contact point. Depth of the cone is measured by the micrometer head. Unlike pin gauges this one reads to 1 µm (.0001 in) accuracy. Use ring gauges to calibrate this type of instrument.

Carbide inserts are featured at the contact points

Inside Micrometers

When the rod is interchanged, the length at left must be checked against a gauge block, XXX or XX ring gauge.



Sweep and rock. Trial and error may be the best way to describe the entire process of finding two opposing points.

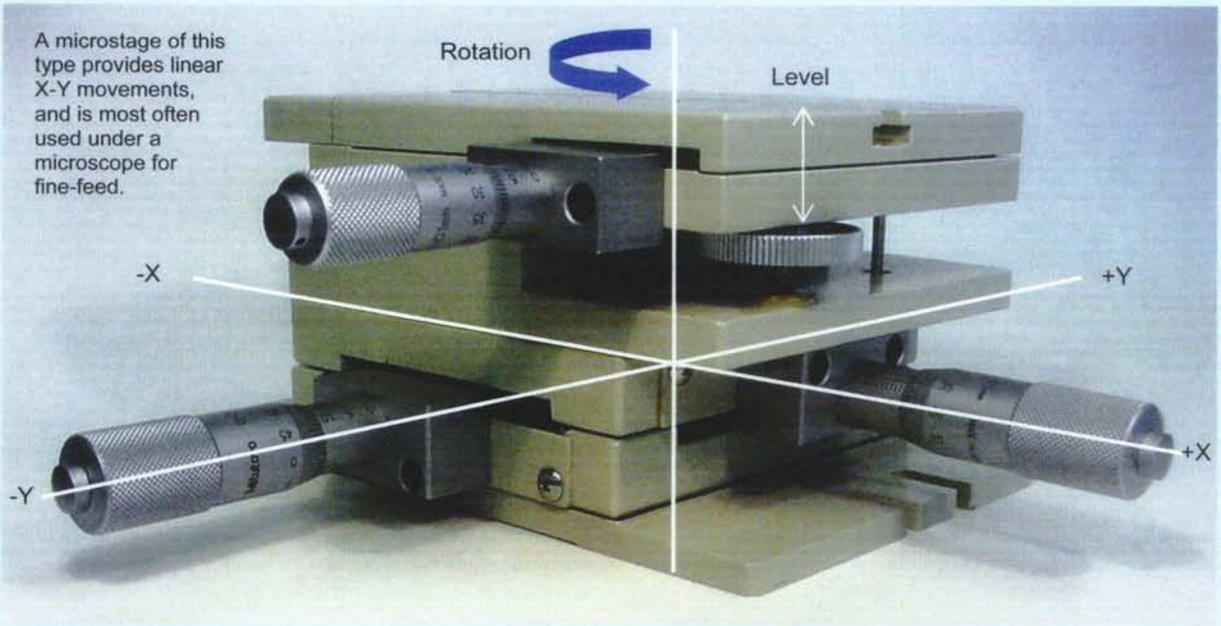
Measuring inside diameters is, in the opinion of many, at least twice as difficult as outside measurements. Ten times more difficult may not be an exaggeration: it seems that no two people can agree or repeat the same measurement twice in a row. The two-point internal micrometer shown above must "sweep" and "rock" in search of the correct inside diameter. In spite of this, this method may be the best way to measure.

Assume the inside diameter between two points, P1 to P2, was measured *(a)*. What about the diameter 90° rotated from there? To find out if it is oval, the gauge must check at least two directions. What if the two collected measurements are different? The diameter may be oval. Sweep the entire internal wall by moving both ends and see if one side is larger than the other.

To measure the diameter by two-point gauge, one end must be at a fixed point, in this illustration *(a)* P1, and the other end P2 must "sweep" and "rock". Patience is required during this process.

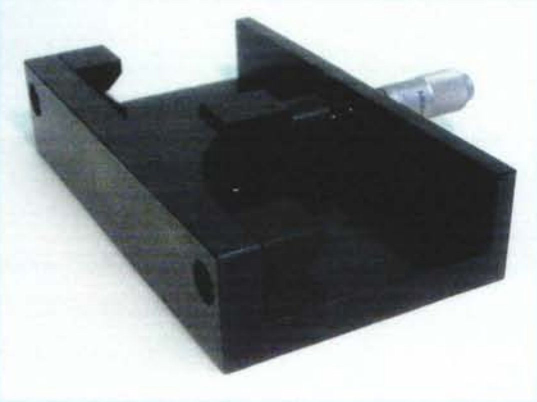
The safe way is to measure the diameter more than once and get an average diameter. At the same time, note the largest and smallest numbers within the multiple measurements. Two-point inside micrometers provide a direct answer between two points whereas the three-point micrometers measure averaged diameters.

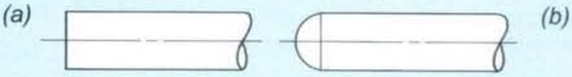
Micrometer Heads


A microstage of this type provides linear X-Y movements, and is most often used under a microscope for fine-feed.

The application at left is used to make rods straight. Straightness of a rod should be checked when it is at 1-to-10 ratio (e.g. bar stock Ø10 x 100 mm long) or more. When a rod is found to be curved, it can be bent back using this tool.

A dial indicator placed in the fixture can find out-of-straightness but it cannot bend it back. The micrometer head will do that. On the end of the spindle is a "V" attachment to hold a rod, and two "V"s on the opposite sides will secure the rod. Turning the micrometer thimble will extend the spindle, bending the rod.

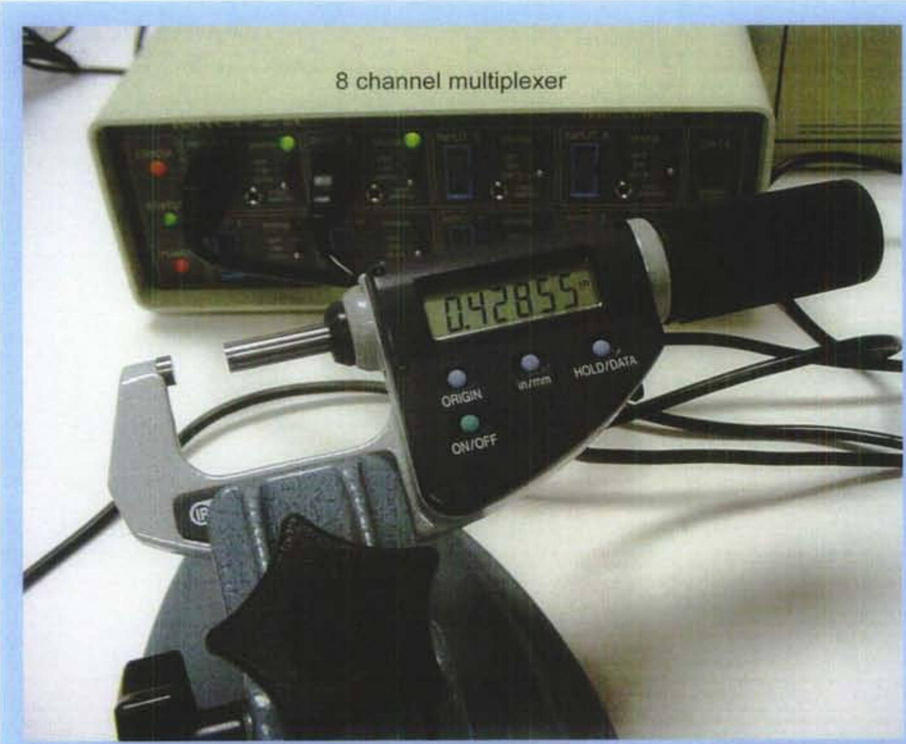




Depending on the application, either flat or ball faces (spherical radius) may be chosen. If the sliding component moves linearly, the flat-faced spindle *(a)* should be sufficient. If the stage rotates, a spherical contact point *(b)* should be the case. The contact surface can be carbide-tipped for wear-resistance.

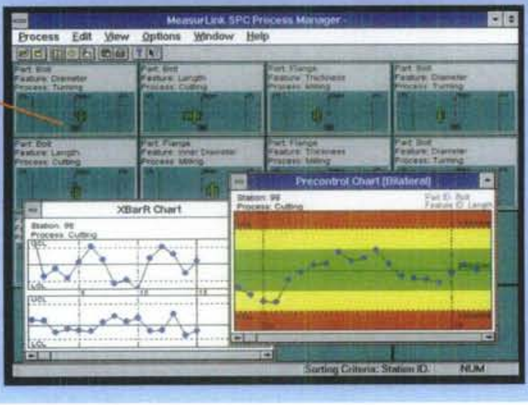
Always rotate micrometer in the "two steps backward and one step forward" tradition. Go backward and then come back so that there is always clockwise movement at the contact point.

Micrometers as Data Gathering Devices

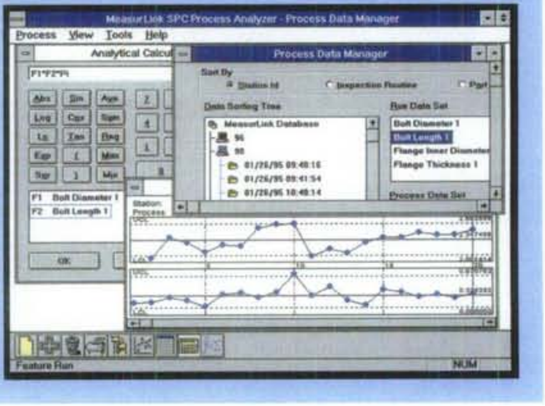


This specific model is a unique linear encoder type which is featured with a miniature linear scale, which allows the spindle to move linearly. It takes only ten turns of the thimble to move it from 0-30 mm (0-1.2 in), the range of this linear-moving micrometer.

(a)



(c)



From the system engineer's point of view, the micrometer is one of the input devices to generate data. The data in turn can be rearranged in such a way that the QC manager's job will become more effective. See the screen above *(a),* it will display nine individual production data (one is obscured by the graph). The screen is constantly prioritised based on the data gathered from the floor. The type of information that requires immediate attention will go to the top left position *(b)*. The QC manager is trained to inspect that corner.

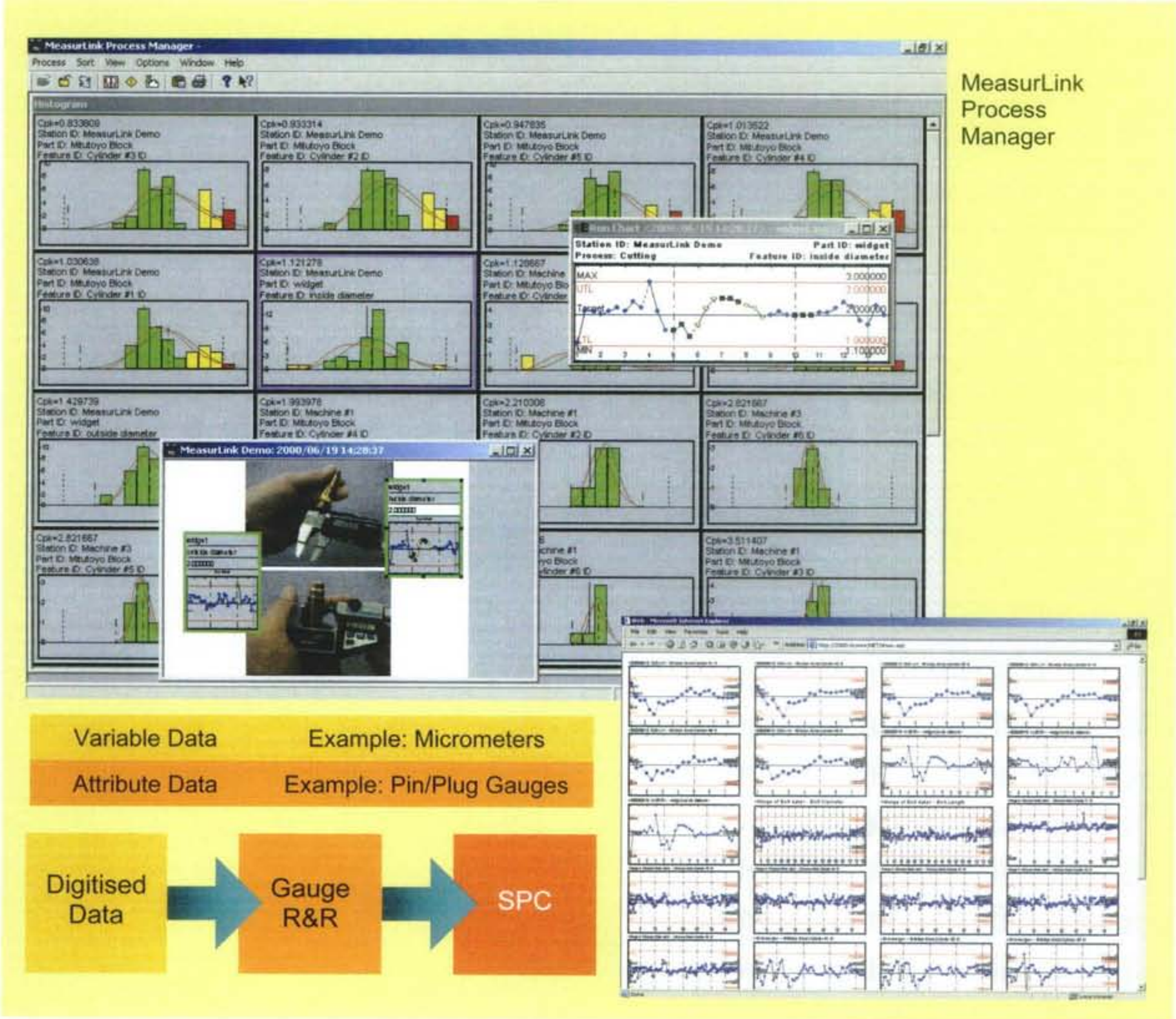
For the system engineer, the software can accumulate valuable data, which can then be stored. Graphs generated from these results can be valuable in identifying various trends in the data *(c)*. This data can later operated on to produce valuable statistics.

Once the data is digitised, the next step is SPC. But before SPC, the quality (trustworthiness) of data must be judged first and quantified. The statisticians at General Motors recognised this and established a method to quantify the trustworthiness of data. In short, only correct data must be entered into the stream of SPC.

Without screening the trustworthiness of the raw data from which a judgment will be made, SPC charts shown on this page would be meaningless. The data must be "true" or as true as possible.

This concern originated at GM during the 1970s and gave rise to the '*MSA (Measurement Systems Analysis) Manual First Edition*' published in 1990 (now MSA Third Edition 2002).

The gauges are known to produce measured data within the stated accuracy. What is unknown is the variance in the data generated by two individuals, operator A and B. Are they producing the same data when they share the same gauge? How much of the data should be trusted? Statistical data can answer many of the questions raised.



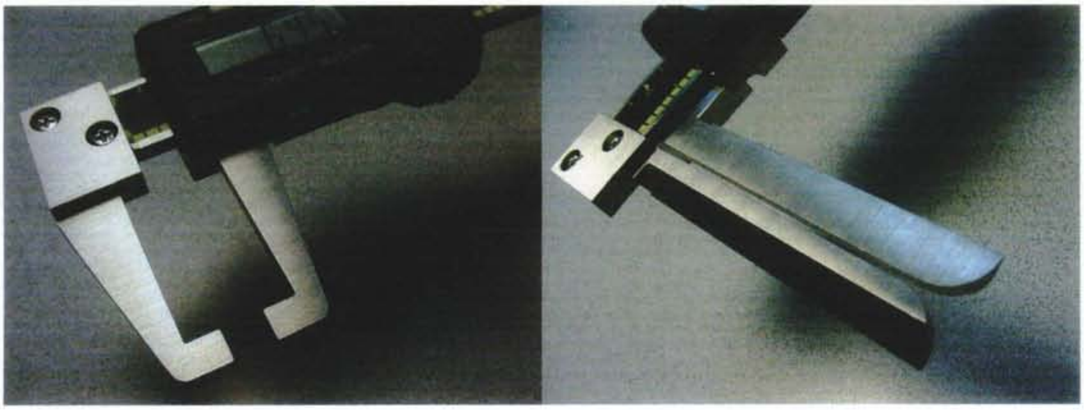
MeasurLink Process Manager

Variable Data	Example: Micrometers
Attribute Data	Example: Pin/Plug Gauges

Chapter

11 Calipers

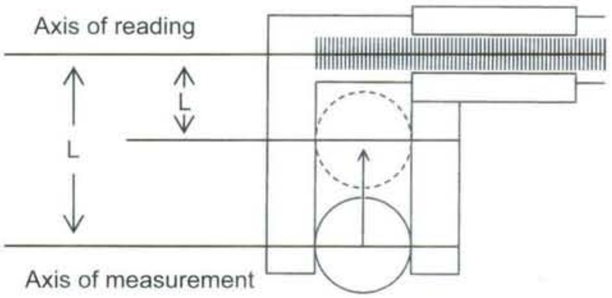
“THE MOST VERSATILE OF ALL GAUGES”



Because of their versatility, ease of operation, durability, and relatively inexpensive cost, the group featured in this chapter, called calipers, are possibly the best tool to have. However due to their design, calipers cannot be immune to the “Abbe’s principle” as outlined below and explained on page 60. The gist of the principle is the further away the axis of measurement is from the axis of reading, the higher the potential error. This rule, however, can be overcome by observing a few simple methods suggested in this chapter.

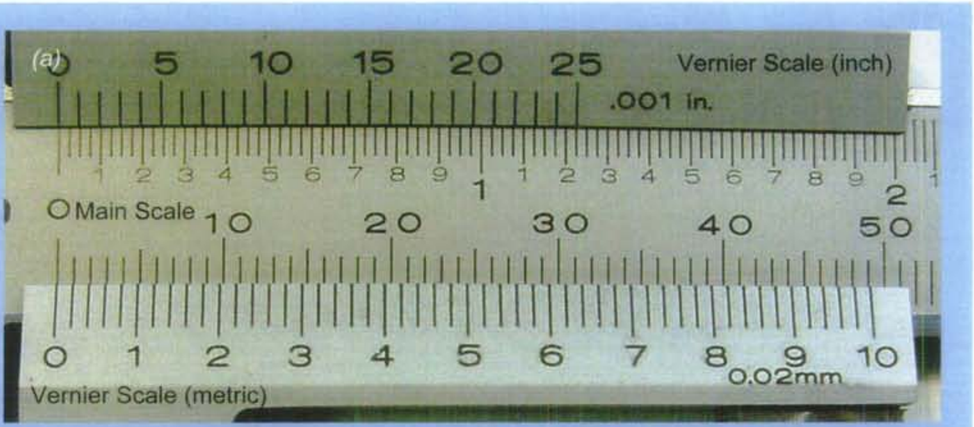
As is shown here, the greater the distance L, the greater the potential error. Ideally, the workpiece should be placed closer to the axis of reading.

The best example of this is the micrometer, where the axis of reading and axis of measurement are shared. This is not the case in calipers, where they are separated.



Vernier Calipers

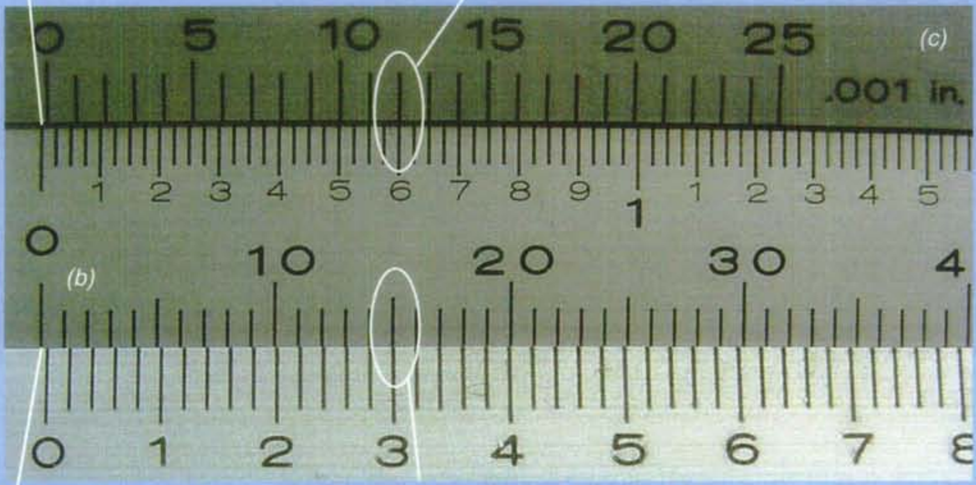
For the metric Vernier Scale, 1mm on the main scale is divided into 50 lines, with each representing 0.02 mm. It is similar for the inch scale, except .025 in is divided into 25 lines, with each worth 0.01 in.



The main scale value is less than .025 in

On the inch scale, the lines coincide at 12, so add .012 in to the main scale reading.

Overall reading = Main + Vernier
.000 + .012 = .012 in



To read the Vernier caliper, first check the main scale value (where the Vernier 0 line is), then add the value of Vernier scale by checking where the lines coincide.

The main scale value is less than 1 mm

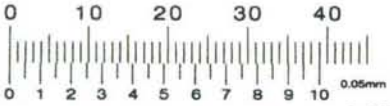
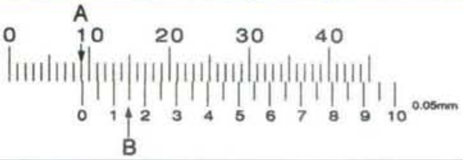
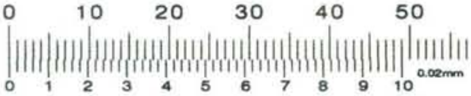
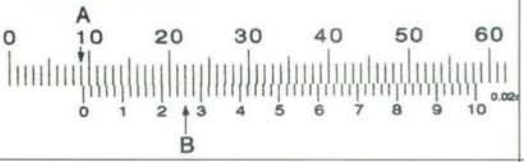
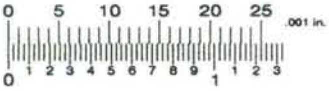
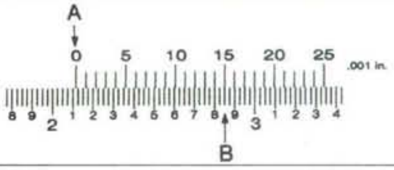
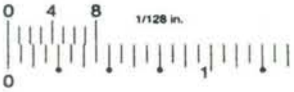
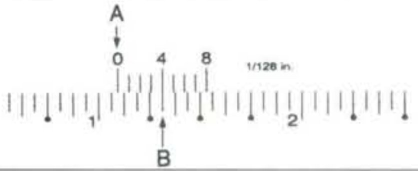
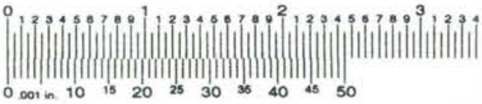
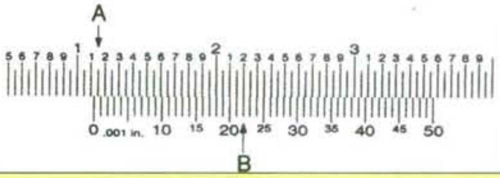
On the metric scale, the lines coincide at 3, so add 0.03 mm to the main scale reading.

Overall reading = Main + Vernier
0.00 + 0.03 = 0.03 mm

Reading the metric Vernier Caliper is easy. It is straightforward, see *(a)* and *(b)*. It is so easy to read that in countries where metric is used exclusively (such as Europe and Asia), few machinists use dial calipers. The key for this ease of reading is in the spacing of lines. The metric scale in the above example *(a)* divides 49 lines (main scale) by 50 lines (Vernier scale). By this combination of 49 over 50, it is easy to locate which two lines meet perfectly. See example *(b)* above. The jaws are open ever so slightly, and the scales are aligned at 3 on the Vernier to indicate 0.3 mm.

On the other hand, the inch scale *(c)* is based on the system of one inch divided into 40 (1/40 in = .025 in), which is used in inch micrometers as well. Each line on the main scale is equivalent to .025 in, which in turn is divided by Vernier scale into 25, thus bringing the smallest reading to .001 in. This practice is solely due to the physical limits of the Vernier plate. Larger Vernier scales are unaffected by this and are just as easy to read as the metric scale.

Reading the Vernier Caliper

Vernier at 0 Point	Vernier Reading Example	Reading
(a)  0.05 mm		A = 9 B = 0.15 = 9.15
(b)  0.02 mm		A = 9 B = 0.26 = 9.26
(c)  .001 in		A = 2.100 B = 0.015 = 2.115
(d)  1/128 in		A = 1-1/16 B = 4/128 = 1-3/32
(e)  .001 in, extended		A = 1.100 B = .022 = 1.122

Of the five examples given above, the least used is the one for inch fractions *(d)*, as it is the most time-consuming to read and most prone to error. And yet tolerances in fractions still exist today (e.g. 11/16, meaning 1/16 smaller than 12/16, which is 3/4 in). The inch fractions are generally replaced by decimal equivalents: .125 for 1/8 and .375 for 3/8 in.

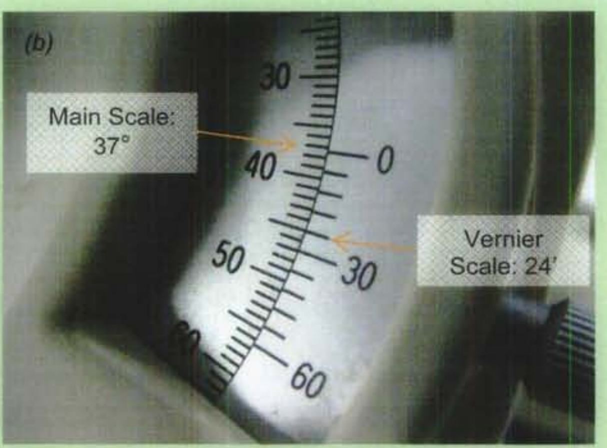
The Vernier Caliper, nonetheless, is as accurate as any other caliper. In real life situations, the calipers' "effective" accuracy would be ±0.05 mm for metric and ±.002 in for inch system.

Note, when the Vernier graduation is extended, it is much easier to read. See examples *(b)* and *(e)* or the graduations *(a)* on the previous page. Larger Vernier calipers are featured with the extended scale simply because the slider is long enough to engrave an extended scale (e.g. 50 lines instead of 25 lines).

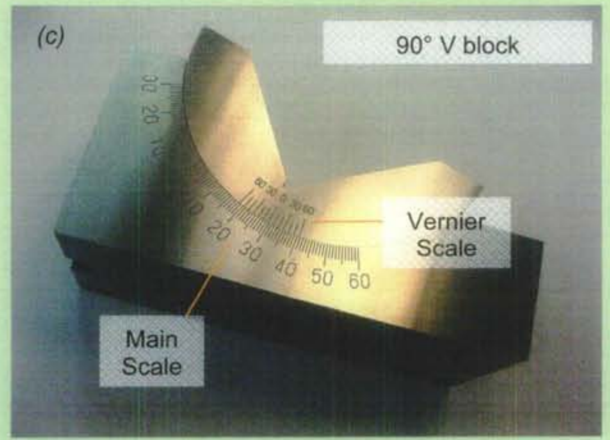
To measure a workpiece such as this, the caliper must be mounted atop it, and it should be measured both north-south and east-west. Some practice may be required until the same values are produced either way

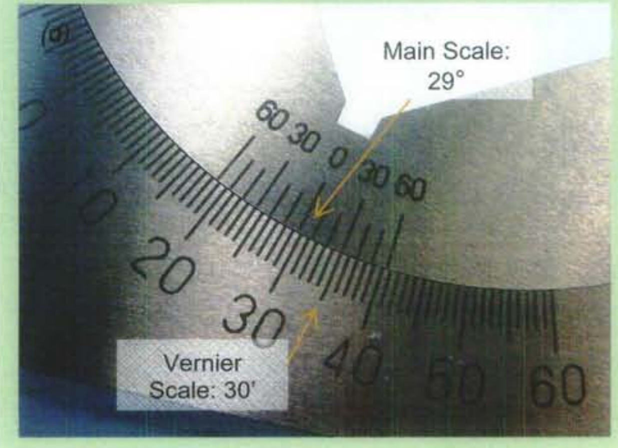
Angle Readings with the Vernier Scale

Magnification is achieved by 2 lenses: this one is called the Eyepiece lens (15X) and the other within is the Objective lens (2X). Combined, 30X magnification provides a clear, detailed view.



The Vernier scale here is read similar to the one present on the caliper: Check where the 0 point intersects the main scale, then check which Vernier inverval is aligned. 37°24' is the reading.



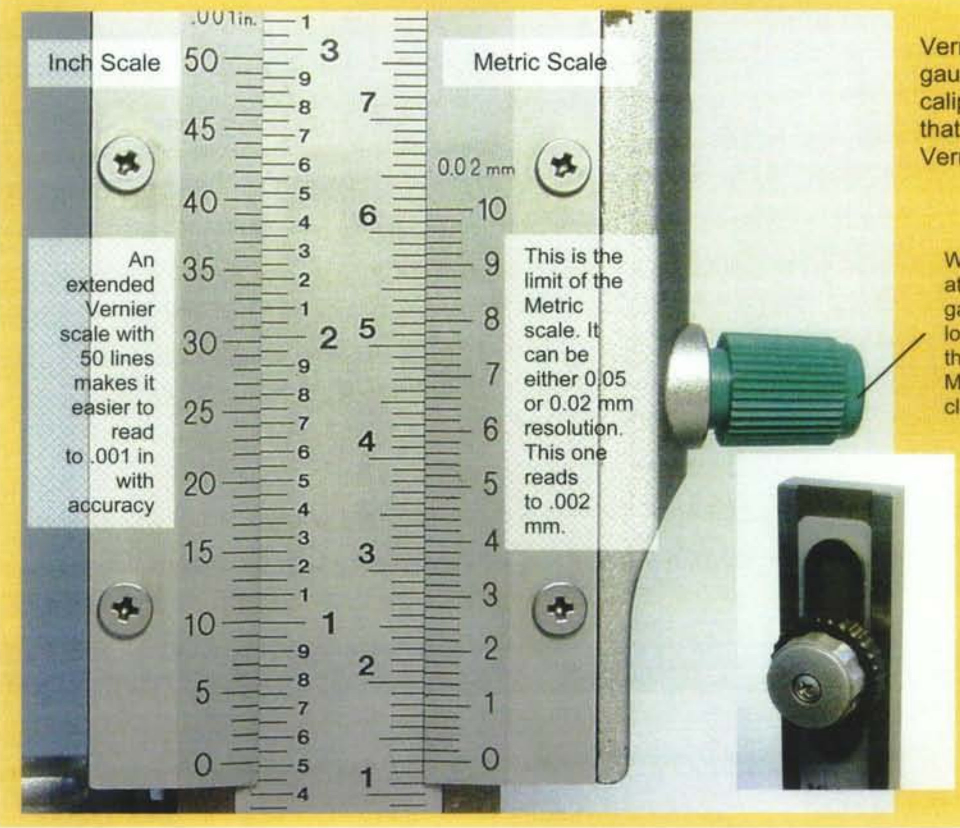


For many years, the Toolmaker's Microscope has been standard equipment for many inspectors and toolmakers. Besides this, Profile Projectors are also used to measure angles, many of which are specified with 1° graduations. This resolution however will not be good enough to check ±1°, where the ratio is 1 to 1. It must be much finer. To increase the smallest angle reading requires a Vernier scale.

See example *(b)* at topmost right. The Vernier scale divides 1 degree into 10 equal parts, or 6 minutes. The fourth line on the Vernier appears to match up with the line on the main scale. Four times six is 24 minutes. The total reading will be therefore 37°24'.

See examples *(c)* and *(d)* at left, which are of a V-block that is made adjustable from 0 to 60°, although the V itself is a solid 90°. The Vernier scale is provided on the inner circle. Its resolution is 10 minutes. This particular angle reads 29°30' (see arrows). As evident in these examples, the resolution of Vernier depends upon how it is divided and by how many lines are used.

Reading Height Gauges



Inch Scale

Metric Scale

An extended Vernier scale with 50 lines makes it easier to read to .001 in with accuracy

This is the limit of the Metric scale. It can be either 0.05 or 0.02 mm resolution. This one reads to .002 mm.

Vernier height gauges are similar to calipers in the sense that they both use Vernier graduations.

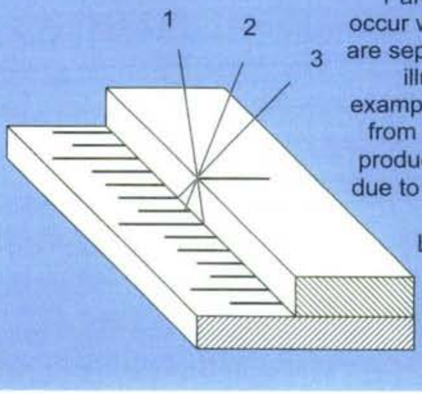
When a test indicator is attached to this height gauge, this clamp will lock the slider and hold the indicator together. Make sure the clamp is tight.

Unlike digital height gauges, Vernier height gauges cannot be zero-set at the push of a button. Instead, the main scale is suspended from the top and slides vertically to adjust its zero line.

Parallax Error

This classic reading error is derived from the fact that the Vernier plate is placed in front of and above the main scale. This may result in "parallax error", since the greater the distance between the scales, the greater the potential reading error due to reading from different angles.

The correct eye point should be where the operator is looking directly into the graduation lines, not from slightly left or right, nor up or down. Unless the operator is exactly on the same level as the lines, an erroneous reading may result. It takes patience to read the scales accurately and correctly, and requires practice to come in directly in order to view the lines.



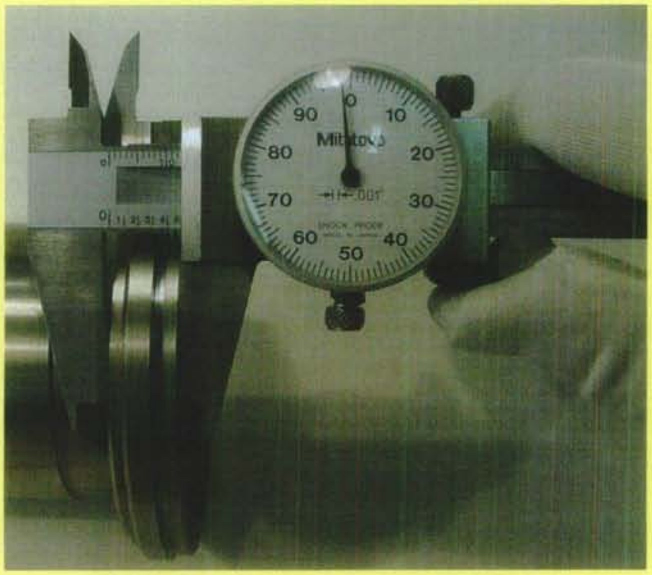
Parallax error is likely to occur whenever two scales are separated by a step, as illustrated here. In this example, viewing the scale from points 1, 2, and 3 all produce different readings due to the angles involved.

Look perpendicularly into the scale to get the reading without parallax error.

Dial Calipers

Resolution .001 in
Accuracy ± .001
(0-6 inch range)

This dimension shown here (.498 in) could have been half inch and allowed to be smaller by .002 in.

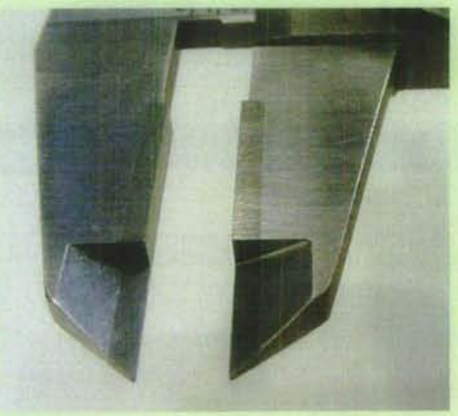


Dial Calipers perform exactly the same as their Vernier counterparts, with the added benefit of being easier to read, especially when dealing with complicated inch fractions, such as example *(d)* on page 163.

Due to complexity in design they are generally more expensive than Vernier calipers, and are less popular in metric only countries, where Vernier calipers pose no problems in reading.

Carbide Jaws on Calipers

Adding carbide inserts to the outside jaws, as shown here, will retard the wear that may otherwise be accelerated by measuring abrasive materials. Carbide inserts may also be attached to the inside jaws.

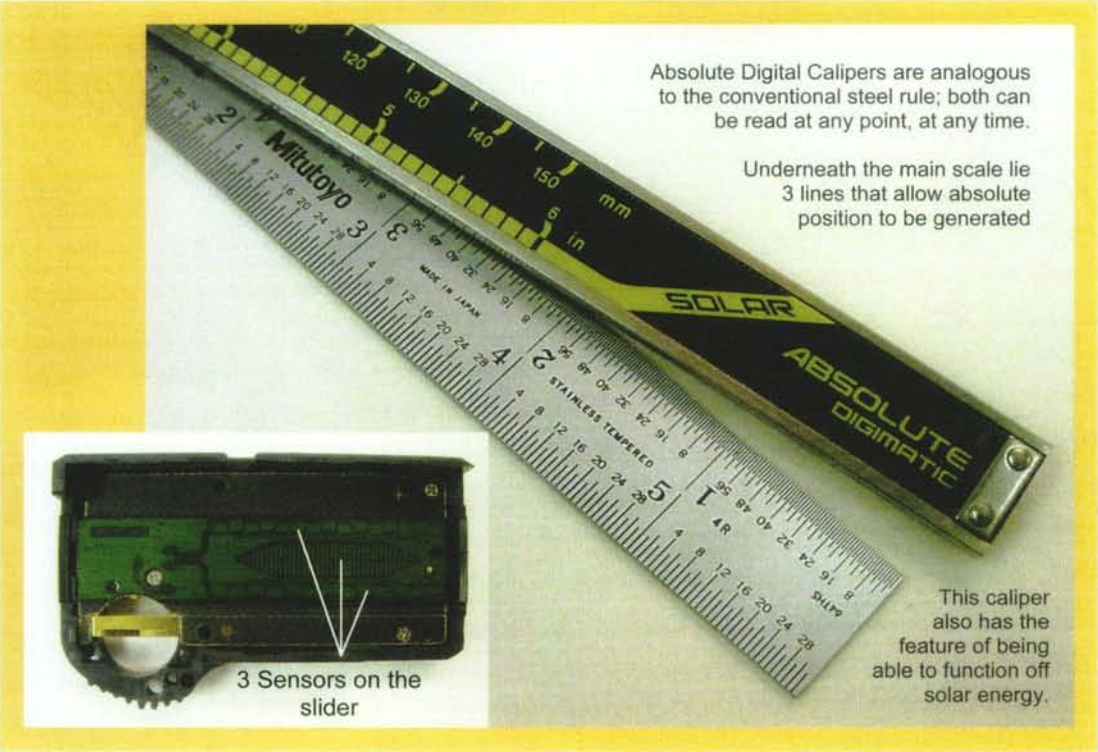


Calipers of all kinds, Vernier, Digital, and Dial, are for general purposes: they measure inside, outside, depth, and even steps. Users of calipers include dentists, scientists, archaeologists, mechanics, machinists, chemists, anthropologists, in short anyone who must take measurements. Having such diverse users and the broadest of applications, calipers sometimes receive harsh treatment. For this reason, most caliper jaws are heat-treated and usually hardened to Rockwell C-scale 62 or better.

Almost all modern calipers are made of this flame hardened stainless steel, which is sufficient for the rigours of normal use. However, when measuring very hard or abrasive workpieces such as grinders and cemented carbide cutting tools, these calipers may still suffer wear. Tungsten-carbide inserts in the jaws should greatly extend the useful life of these calipers by improving on the hardness.

If outside jaws (without carbide inserts) are bent, they can be restored to the original condition by a disc-shaped lapping stone inserted between the jaws and removing the excessive stock, thus restoring the parallelism between the outside jaws. Inside jaws may be heated and bent back by service technicians.

The "Absolute" Caliper



Absolute Digital Calipers are analogous to the conventional steel rule; both can be read at any point, at any time.

Underneath the main scale lie 3 lines that allow absolute position to be generated

This caliper also has the feature of being able to function off solar energy.

3 Sensors on the slider

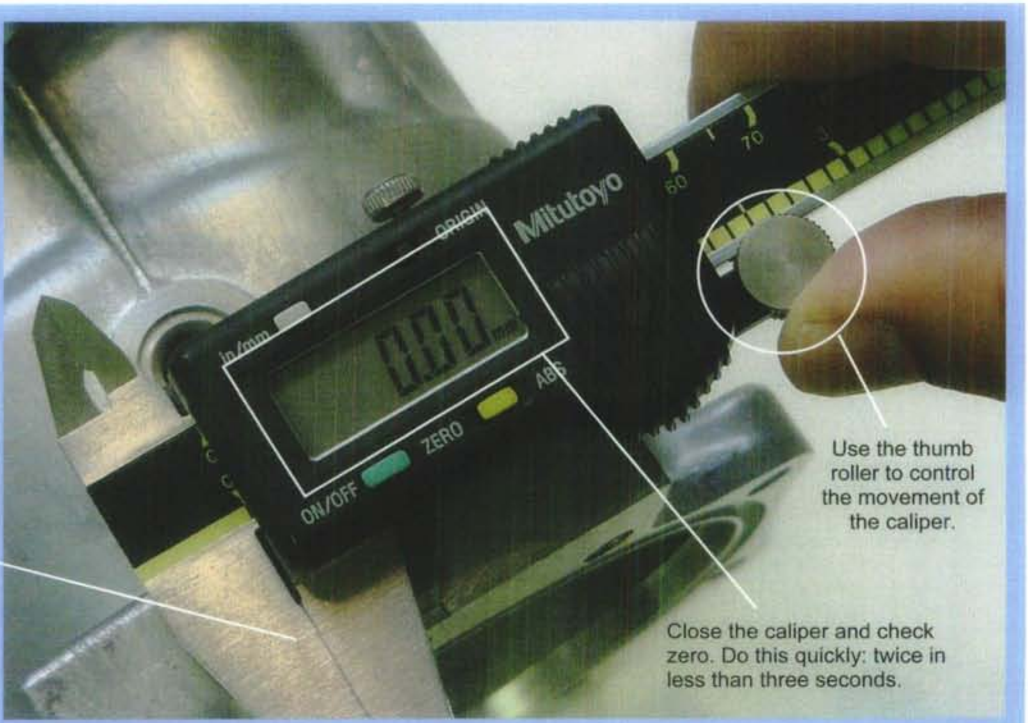
Conventional digital calipers make use of a basic binary system: they have a series of light and dark bands or plus/minus signs under the slider, and count one every time they move along the track. Because of this system it is necessary for most digital calipers to first close the jaws and check zero is displayed before moving the jaw, allowing the binary system to initialise and start counting the numbers.

As the Vernier Caliper design could read any point within its range without going back to zero, this digital caliper reading system seemed cumbersome. This changed with the introduction of the "Absolute" digital caliper, which could read the jaw location at any position without needing to return to the original zero.

According to one school of thought, the best caliper is still the old-fashioned Vernier Caliper. Vernier calipers are simple to use, inexpensive, and just as accurate as the latest digital calipers. However it is undeniable that they are hard to read at times (particularly the inch scale) and cannot convert seamlessly from inch to metric and vice versa. The "Absolute" type digital calipers take advantage of the best of both worlds: analogue and digital.

The "Absolute" digital caliper makes use of 3 sensors within the slider and 3 corresponding tracks embedded in the main beam. As the slider moves, it can read the position of the tracks under these 3 sensors and calculate its current absolute value. This eliminates the need of having to reset the caliper first, and thus the hassle associated with conventional digital calipers.

Measuring Methods



Always check zero before and after measuring.

Make sure the jaw faces are clean. Put a piece of paper between the jaws and pull it away to clean them.

Use the thumb roller to control the movement of the caliper.

Close the caliper and check zero. Do this quickly: twice in less than three seconds.

1 Close the caliper. Put the jaws together and check zero. Repeat this two to three times.

2 Always measure more than once. The first measurement is generally poor. Disregard it and measure again.

3 Close the calliper again. Check if zero is still there. Always begin and end with checking zero.

Open the jaws slightly and then close them. Repeat this process few times, making sure the LCD indicates zero every time, spending no more than a few seconds on this check. If the caliper is of the ABS type (for "ABSsolute" reading, as above), zero setting is not required. Nevertheless, to make certain it is operating correctly, close the jaws and check zero.

Now you are ready to take measurements. Make sure more than one measurement is taken, because the first one tends to be a poor measurement. Continue to measure until the data starts to repeat itself. In the example shown here, this digital caliper starts to read the same data 73.88 after the third trial. You can disregard the first and second readings as incorrect.

Trial	Measured Value
1	73.90 mm
2	73.89 mm
3	**73.88 mm**
4	**73.88 mm**
5	**73.88 mm**

Measuring with a caliper should take only three to four seconds. The caliper must be wiggled or aligned to find the right orientation against the work surface. Pressure must be lightly applied: Touch the workpiece and back off, touch again and back off.

"Wiggle" the caliper while pushing the caliper lightly on the thumb roller. Back off by opening the jaw then closing it again, repeating until the LCD display starts to show the same reading.

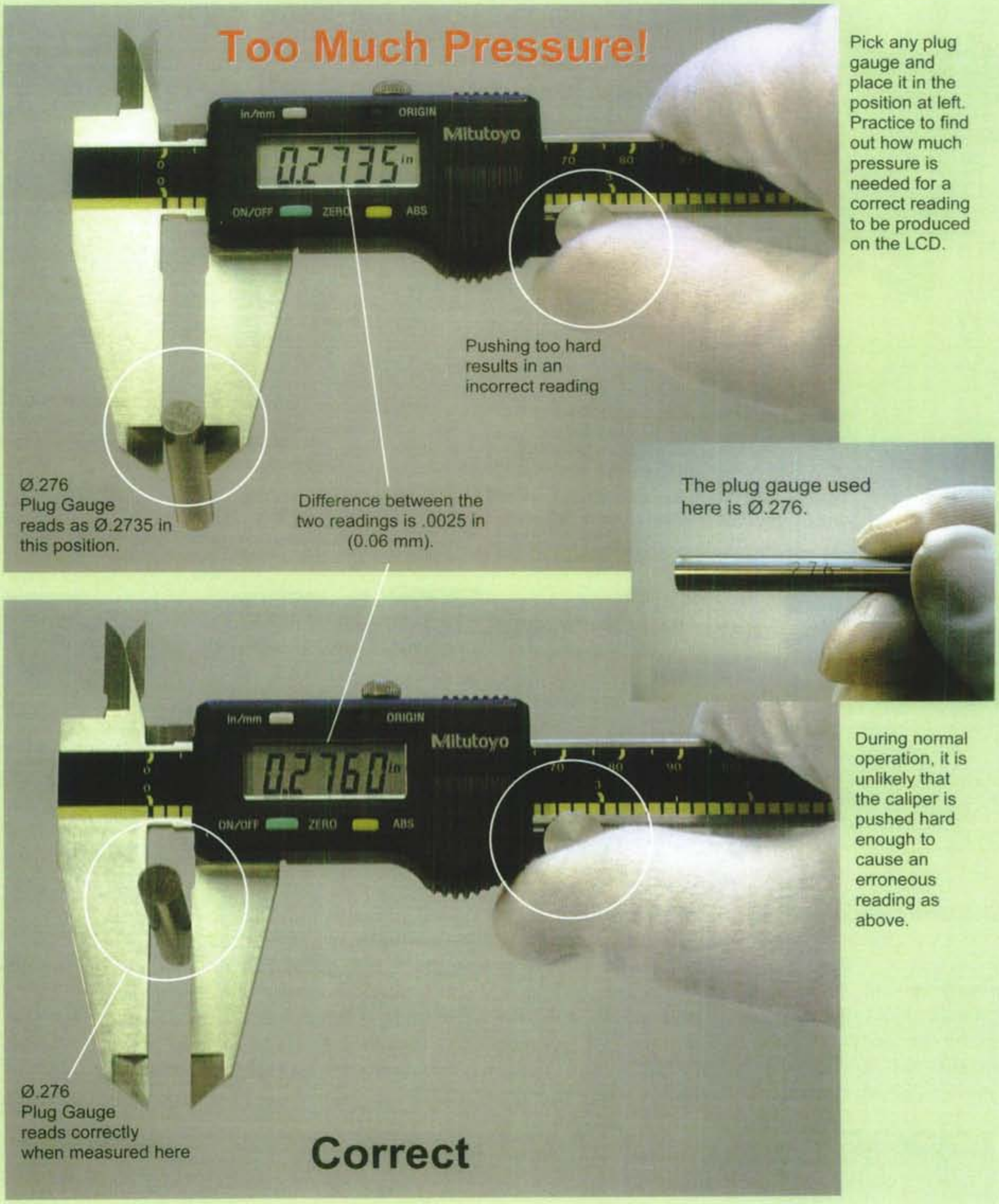
This machined surface does not appear critical, nonetheless check the blueprint. It may be acceptable to use a caliper if tolerance is not very tight (e.g. 0.05 mm area). If the tolerance presented is much tighter than this, this dimension must be checked by a micrometer. It is always a good idea to find out what this dimension roughly should be first.

The right answer should be the smallest value read when trials are repeated. Larger values are caused by jaw and workpiece misalignment.

Theoretically speaking, if the jaws and the workpiece are oriented correctly, the right answer should be the smallest measured dimension within repeated trials; larger dimensions are due to misaligned jaws. Assuming that 73.88 is the right answer, the operator should be able to validate it by repeating the measurement. Soon, he or she will be convinced that 73.88 is the right answer and 73.90 is not, as to read values other than 73.88 becomes difficult after a few trials. If the caliper does not repeat, then the operator is not using the same pressure. For a hand tool such as this, it is through the way it is handled that produces the right answer. Personal bias from one operator to another may amount to as much as 50 μm (.002 in). With practice it should come down to zero.

Rule of Thumb 1	Rule of Thumb 2
Do not trust your first measurement (It is usually poor)	Do not trust your measurement unless you can repeat it

How to Measure Correctly with Calipers



Too Much Pressure!

Pick any plug gauge and place it in the position at left. Practice to find out how much pressure is needed for a correct reading to be produced on the LCD.

Pushing too hard results in an incorrect reading

Ø.276 Plug Gauge reads as Ø.2735 in this position.

Difference between the two readings is .0025 in (0.06 mm).

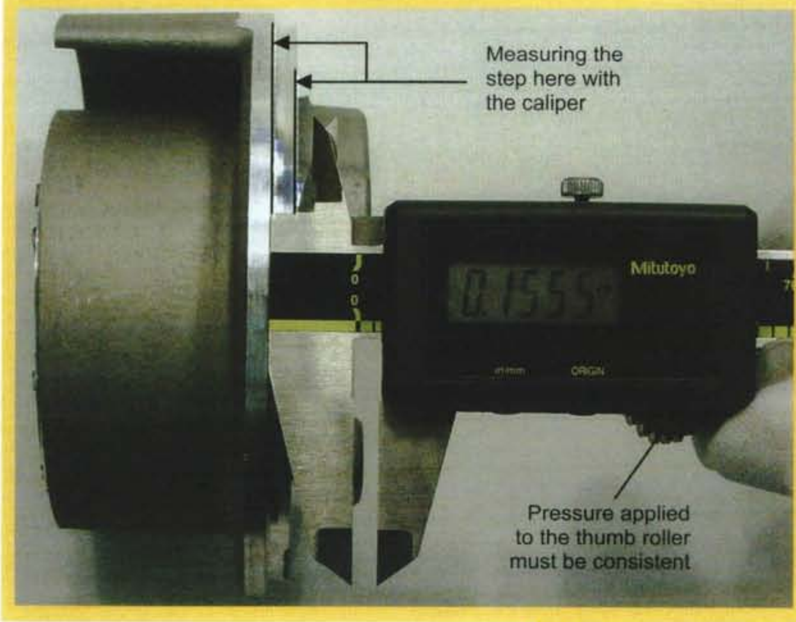
The plug gauge used here is Ø.276.

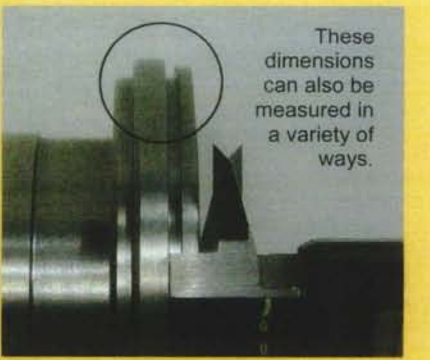
During normal operation, it is unlikely that the caliper is pushed hard enough to cause an erroneous reading as above.

Ø.276 Plug Gauge reads correctly when measured here

Correct

Step/Depth Measurements





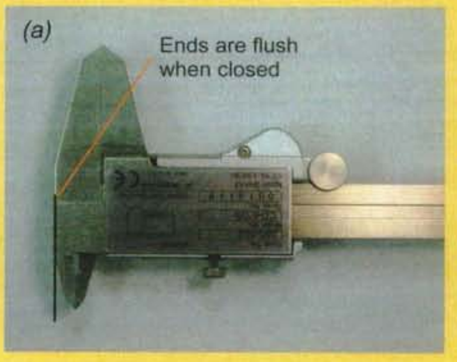
The best instrument to use to measure these dimensions is of course the depth micrometer, but the caliper may be a close second choice. Calipers are versatile in their uses, but at the same time require a certain level of skill to produce reliable readings.

Given a choice, the depth micrometer is the most suitable for this purpose because they are much more accurate. However if the measurement is meant to be rough and done quickly, a logical second choice should be the caliper.

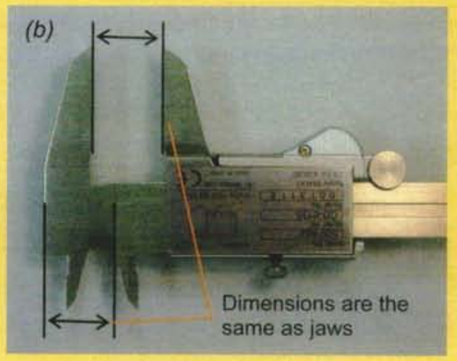
Calipers require more skill to operate than any other hand-held gauge. More often than not they produce slightly different readings every time they measure. The amount of pressure applied is the difference, and practice by repeatedly measuring known pin gauges will allow operators to find out how little pressure is needed to get the correct reading. Pin gauges are length standards, and thus are more accurate than calipers.

Unlike depth micrometers which measure better than 10 µm (.001 in for inch models), the resolution of calipers is limited to 20 µm for Vernier calipers at best. Digital calipers such as the one shown above read to 10 µm. Measured by skilled machinists, the measured data repeats well. The skill level of the operator has a lot to do with the trustworthiness of the data.

(a)



(b)

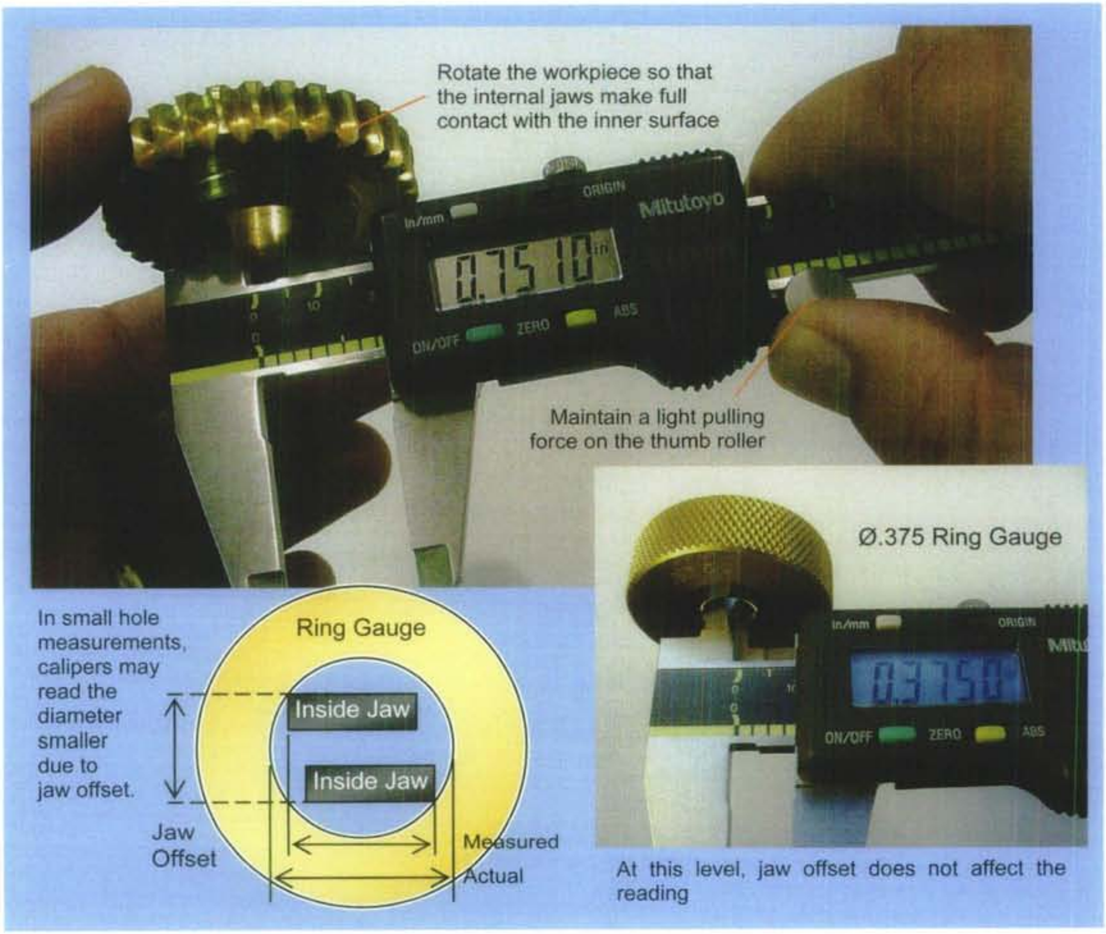


Though the other end is not shown here, both left and right ends of the caliper are ground flush.

When the jaw slides from its closed position, so does the end of the slider as in *(b)* at left. This dimension is the same as that of the outside jaws.

This method is far more stable than the other method, which is to use the depth bar on the opposing end.

Measuring Small Holes



Rotate the workpiece so that the internal jaws make full contact with the inner surface

Maintain a light pulling force on the thumb roller

Ø.375 Ring Gauge

In small hole measurements, calipers may read the diameter smaller due to jaw offset.

At this level, jaw offset does not affect the reading

Measuring small holes with the inside jaws is not a strong feature of any caliper. Smaller than Ø4 mm (Ø.157 in) in hole diameter may be slightly affected by the inside jaw offset as illustrated above. A ring gauge can be used to check where this offset starts to take effect. Note, the ring gauge accuracy is superior to that of a caliper. Bear in mind ring gauges are available in six accuracy categories: XXX, XX, X, Y, Z and ZZ. To make sure small internal diameters are measured correctly use XX or XXX class ring gauges (See page 117 for more details). As shown in the table below, double-X ring gauges are far more accurate than digital calipers. Triple-X ring gauges are even more accurate.

Accuracy Comparison	
XX-Class Ring Gauge	0.5 µm (.000020 in)
Digital Caliper	±20 µm (±.001 in)

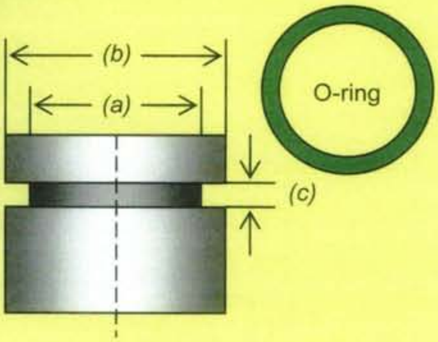
Inside jaws are calibrated against flat and parallel walls represented by blocks at the factory. Narrow parallel slots are not affected at all.

To measure internal diameters, remember to keep on rotating the workpiece whilst lightly pulling at the thumb roller, to ensure that the inside jaws make full contact with the internal surface.

Measuring Narrow Grooves

The outside jaws have thinner edges in order to measure inside narrow grooves.

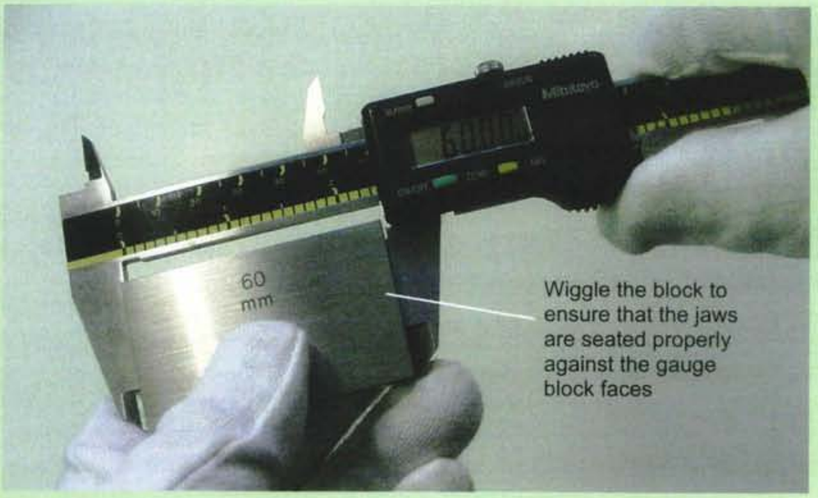
A groove such as this one (below) must be designed to accept a sealant or O-Ring. If so, both *(a)* and *(b)* must be measured in addition to the groove width *(c)*, for the O-ring must protrude slightly from the groove to function as a seal.



The edges of the outside jaws are made thinner so that narrow grooves such as this example can be measured. The overall jaw thickness is approximately 3.5 mm (.138 in) whereas the edge is ground to 1 mm (.039 in). In many cases this is just enough to clear the shoulders and get into the narrow groove where O-rings may be inserted.

If this dimension is above and beyond the ±0.02 mm (±.001 in) accuracy of a caliper, then other methods should be considered. A Profile Projector at 10X or 20X magnification may be suitable. Also, after the O-ring is inserted, it will deform within the narrow groove. That condition may also be clearly seen on the projected screen.

Checking Outside Jaws

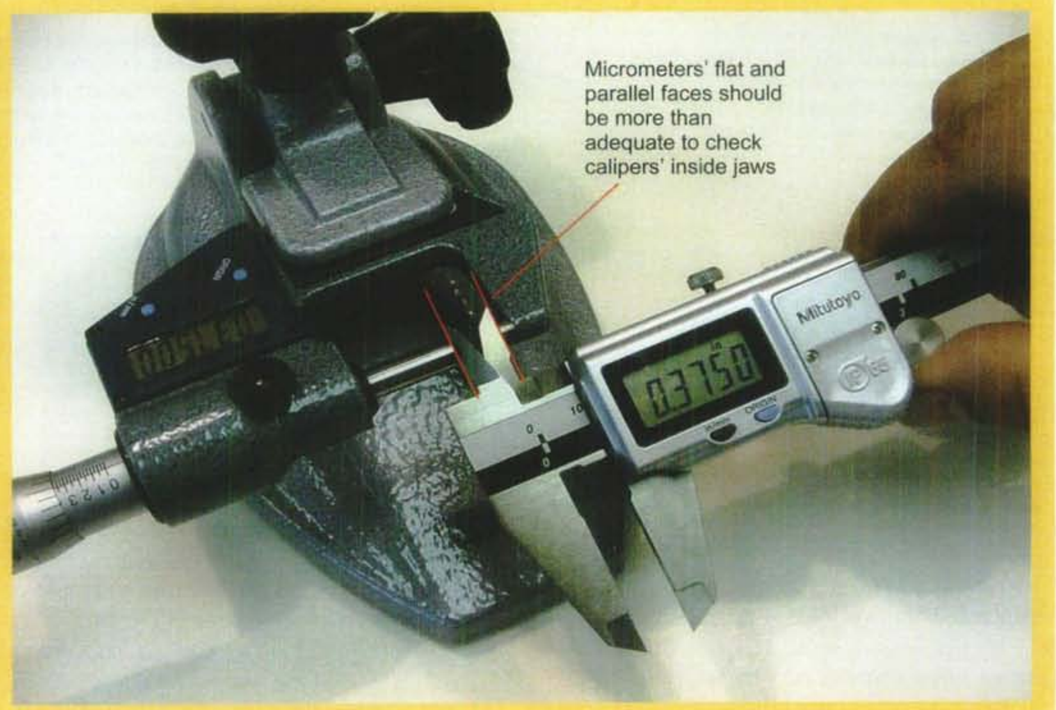


Wiggle the block to ensure that the jaws are seated properly against the gauge block faces

Periodically, calipers are checked against gauge blocks.

Always remember to check zero before and after measuring the blocks.

Calibrating Calipers



Micrometers' flat and parallel faces should be more than adequate to check calipers' inside jaws

Micrometer accuracy: ±.0001 in

Caliper accuracy: ±.001 in

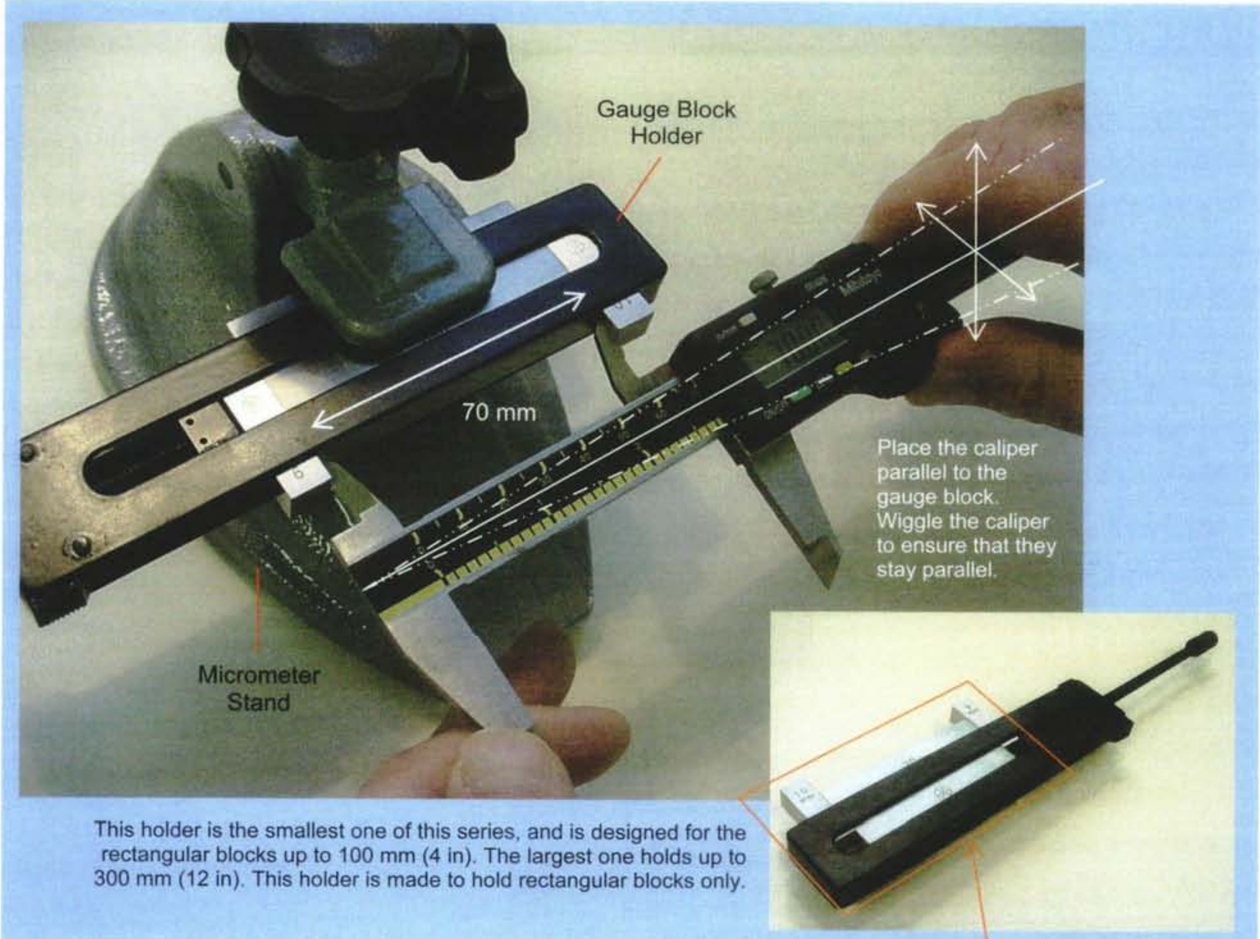
Therefore the 4 to 1 rule is preserved, as the ratio between the two is 10 to 1.

The calipers' inside jaws are for measuring slots and other similar features where the walls are straight and parallel to each other. The ideal slot, both flat and parallel to each other can be found in a micrometer which is at least 10 times more accurate than a caliper. The best method, without a doubt, is to use gauge blocks for calibrating any gauge, including micrometers. However, when they are not available, a micrometer can be used as an alternative standard, as the ratio of accuracy between the two is 10:1. A micrometer, whether digital or analogue, is still more accurate than a caliper: regardless if digital, dial or Vernier.

The accuracy ratio between gauge blocks and calipers would be almost 500:1. Even though the best way to calibrate is to use gauge blocks, this may be overkill in most cases. The micrometers' accuracy, having more than 10:1 advantage over calipers, should be sufficient for checking inside jaws. In addition to that, micrometers are inherently superior in construction over calipers as they have zero "Abbe" offset.

While this point may be argued by some, only one checking point (any point) should be sufficient for the calipers' inside jaws. The rest can be calibrated by the outside jaws instead. For example, 150, 100, 50, 25, 10, 8, 6, 4, 2, 1 mm or their inch equivalents may be calibrated with the outside jaws.

See the caliper above one more time. This caliper is an inch-metric dual reading caliper. Question: which is correct, check inch, or check metric, or both? The answer is to check inch readings and disregard metric. Reason: This caliper works in metric first and converts metric into inch equivalents; inch is thus a translated value. If inch is found to be good enough then metric should automatically follow. On the other hand, if measurements are done solely in metric, calibrate in metric.

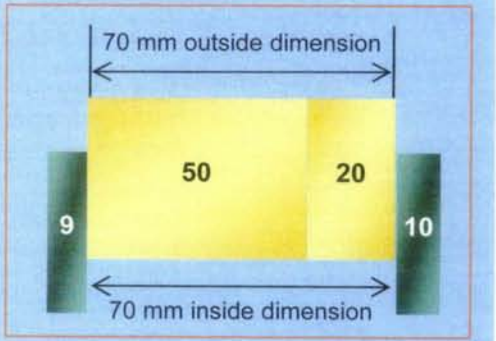


Place the caliper parallel to the gauge block. Wiggle the caliper to ensure that they stay parallel.

This holder is the smallest one of this series, and is designed for the rectangular blocks up to 100 mm (4 in). The largest one holds up to 300 mm (12 in). This holder is made to hold rectangular blocks only.

Gauge Blocks are the true embodiment of most precise length, representing the highest level in the traceability hierarchy. There is nothing above gauge blocks except the wavelengths of red Helium-Neon laser at the National Institute of Metrology level. At any manufacturing plant, gauge blocks represent traceable standards of length.

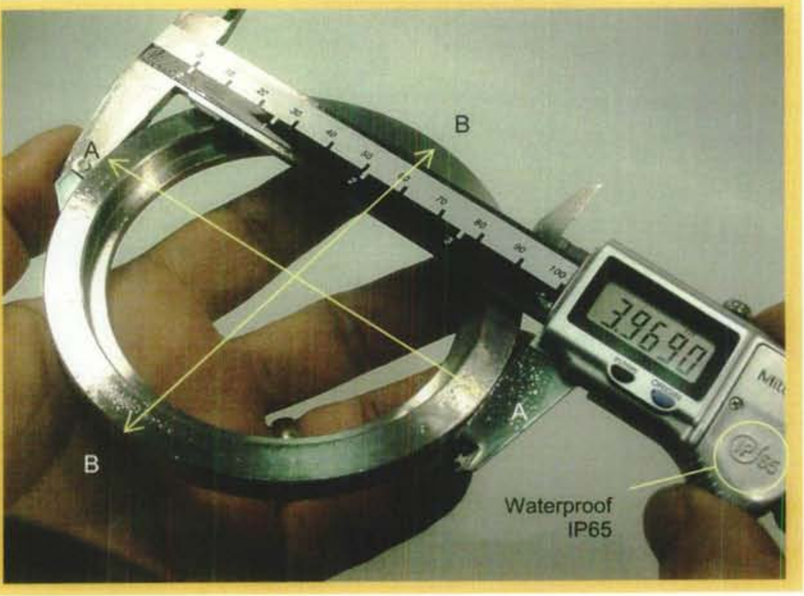
The clamping holder for gauge blocks shown here is a specially designed holder for rectangular gauge blocks. It will keep wrung and stacked blocks together. It must be noted that the gauge blocks must be wrung first, and that this holder will not assist in the wringing process. Square blocks need no holder because they are featured with a through hole and connecting rods are available to put them together. The micrometer stand shown above is a useful equipment holder not only for micrometers but also for other flat objects or standards. Any strong vise will also do the job, provided that they do not scratch the blocks in the process.



This close up of the way in which the gauge blocks are arranged in the holder shows how both the inside and outside jaws of a caliper can be calibrated. The 10 mm and 9 mm blocks here serve as spacers.

To compare, the caliper must be placed parallel to the gauge block. Wiggle the caliper to ensure that the caliper is parallel to the blocks. Both inside and outside jaws can be calibrated this way.

Waterproof Digital Calipers



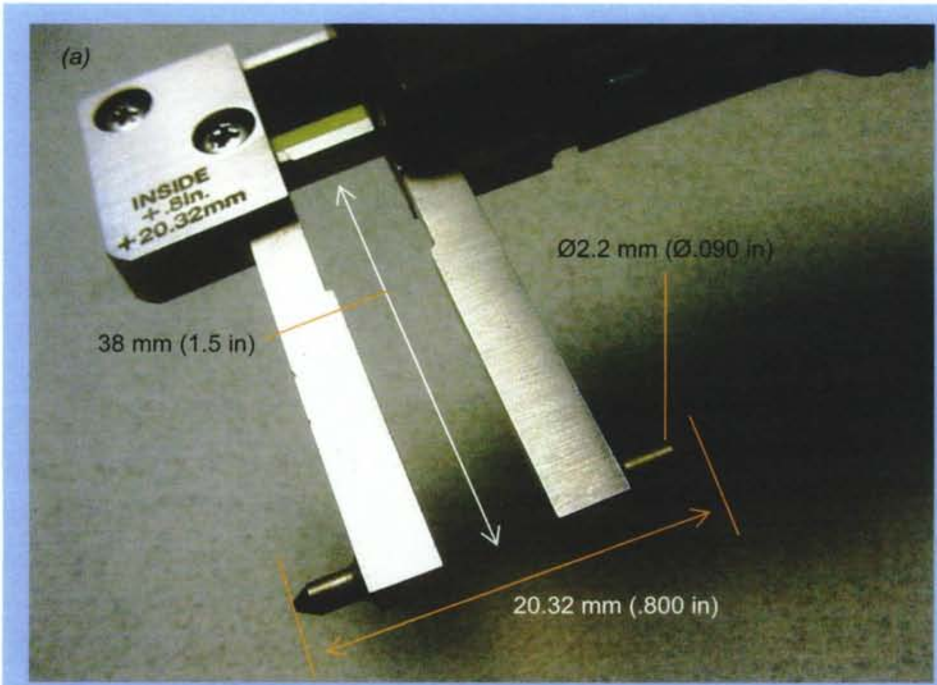
To accurately measure the major and minor diameters, always measure in 2 directions: A-A and B-B. This part may be out of round by 50 µm or more.

This model of caliper is also waterproof, as even though there are drops of coolant on the jaws and main scale, it continues to function.

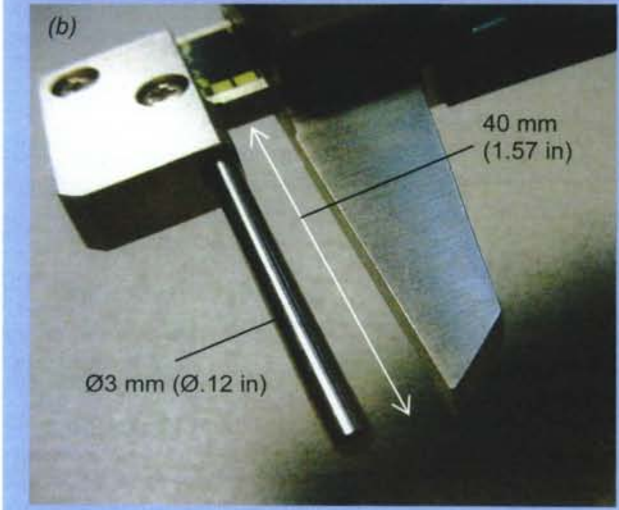
This designation, "IP", was established to quantify in numbers the degree of dust and waterproofing incorporated in instruments. As shown below, IP 66 is the best number. This water-proof caliper is rated as IP 65, and some of the latest Mitutoyo digital micrometers are rated as IP 54.

	First IP Digit		Second IP Digit		
	Type	Definition	Type	Definition	
1	Large foreign matter protective	Protects against the entry of solid foreign matter with a diameter over 50 mm	Drip-poof Type I	Not subject to adverse effects from drips that come perpendicularly	1
2	Middle foreign matter protective	Protects against the entry of foreign matter with a diameter of >12 mm	Drip-poof Type II	Not subject to adverse effects from drips that come within the 15° range	2
3	Small foreign matter protective	Protects against the entry of foreign matter with a diameter of 2.5 mm or more	Rain-proof	Not subject to adverse effects from rainfall that comes within 60°	3
4	Particulate foreign matter protective	Protects against the entry of solid foreign matter with a diameter of 1 mm or more	Splash-proof	Not subject to adverse effects from splash that comes in any direction	4
5	Dust protective	Protects against the entry of harmful dust (permits dust that will not affect the function)	Jet-proof	Not subject to adverse effects from direct jet of water from any direction	5
6	Dust tight	Completely protects against the entry of any dust & against human body contact	Water-resistant	Protects against water in a direct jet that comes in all directions	6

Specialised Jaws for Specialised Purposes

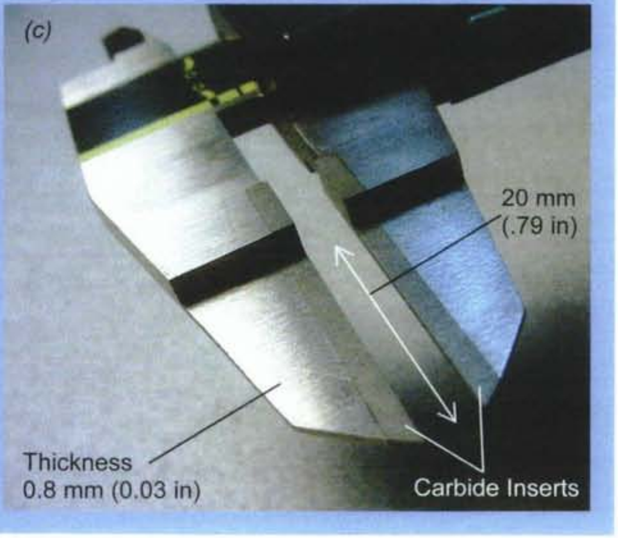


Here are three examples of calipers featuring specially constructed jaws. See *(a)* at left, this is a specialised caliper to check internal groove depths where O-Ring or washers may be inserted.



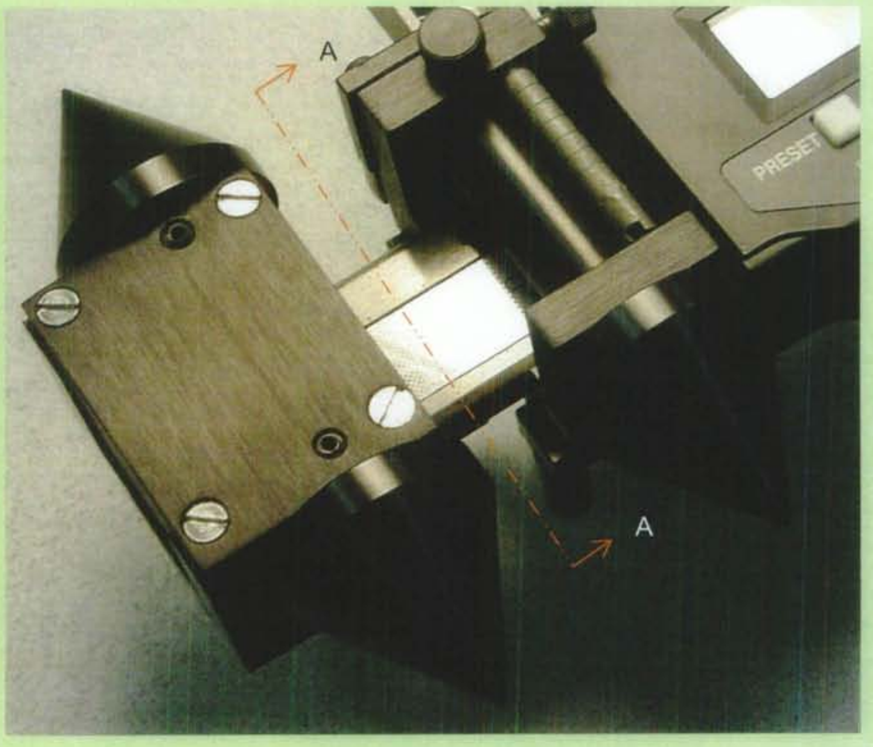
Caliper *(b)* is used to measure the dimension between small holes and a plane. It fits holes larger than Ø3 mm (Ø.12 in). Because of its length, keep in mind not to apply too much pressure while measuring to get an accurate reading while using this special purpose caliper.

Example *(c)* below features ground down thin jaws. Diameters of thin slots are usually measured by blade micrometers, but they are limited to 25 mm (1 in) range. This special caliper *(c)* having 150 mm (6 in) range may be more useful because of its large range alone. In order to withstand heavy usage, the outside jaws are fitted with carbide for longer tool life.



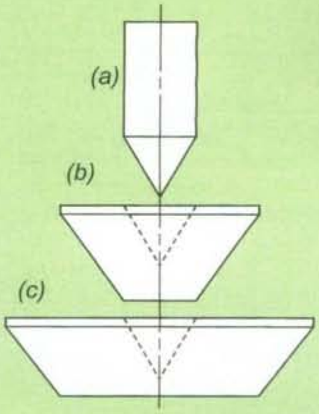
Caliper Attachments

Cone Attachments are for measuring Hole-Centre to Hole-Centre distances



View A-A:
The "Floating" Metal Scale

Graphite beam reduces weight



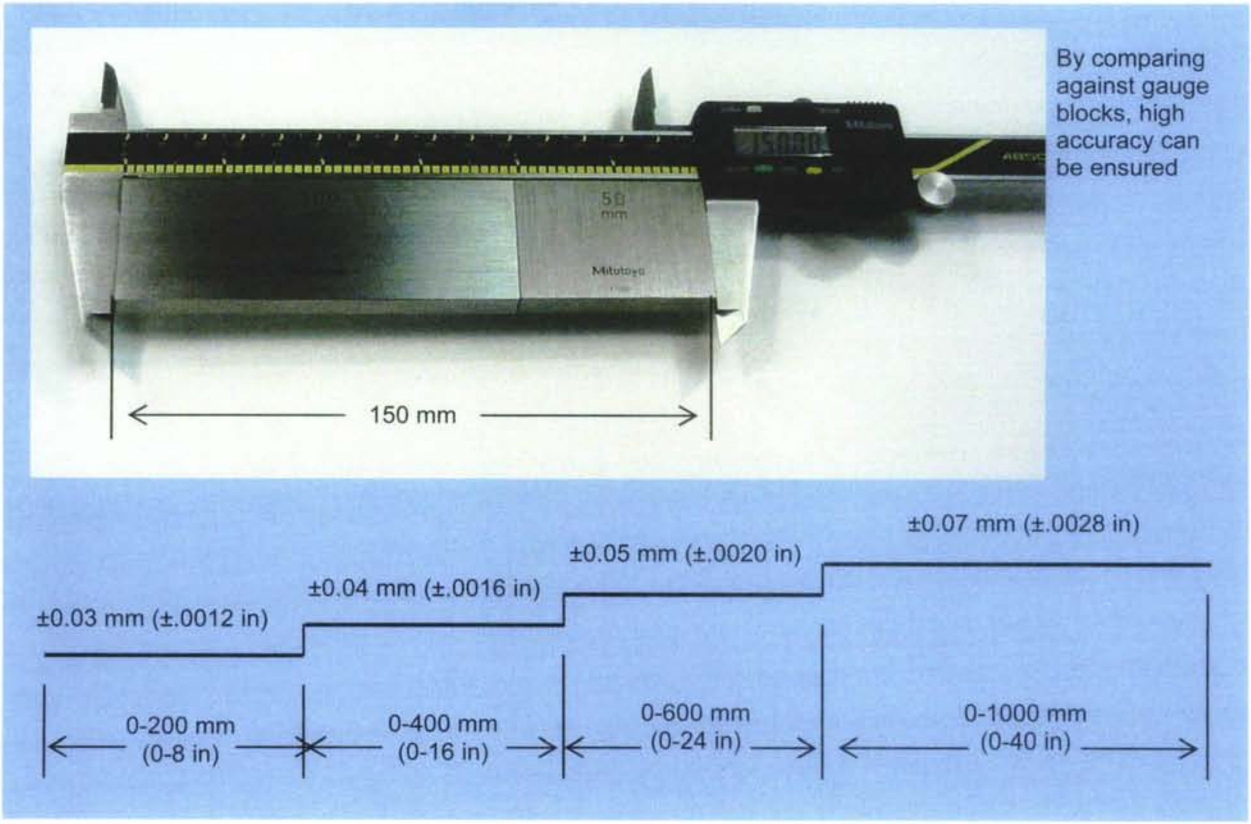
As shown here, the cones are designed to fit on top of each other *(a)*, *(b)*, and *(c)*, and increase size by doing so. "Cone Extenders" they call them. The largest diameter where the largest cone can be seated is Ø92 mm (Ø3.62 in)

Distance between hole centres are best measured by a CMM. They are usually located in an air-tight QC room and cannot be moved onto the shop floor. However on the production floor, a variety of quick and correct decisions have to be made at short notice so that the machines can keep on working — a common occurrence.

Centre-to-centre distance may be predetermined by multiple drills that may produce a dozen holes in one quick motion. If the distance in question is not super-critical, then this type of gauge may be considered. The level of accuracy attained from this system would be in the neighbourhood of 0.05 mm (.020 in). Despite this limitation, or within this limitation, the caliper with cone attachment does a credible job of quickly assessing the hole-to-hole distances without needing to bring the workpiece over to the QC room where the CMM may not be immediately available. The key here is quick and easy. If this is what is required, this caliper may be the answer.

There are several models, and the longest one can go as far as 0-2170 mm (0-80 in): at that length the whole caliper is too heavy to handle by a single person, let alone to measure centre-to-centre distance. To alleviate this condition the entire beam is made of rigid but light graphite. The scale is isolated from it and floated, so that it cannot be affected by the non-metal thermal expansion. Accuracy is ±50 µm (±.002 in) for the 600 mm (24 in) model and it decreases proportionally thereafter.

Caliper Accuracy



By comparing against gauge blocks, high accuracy can be ensured

As shown above, the instrumental error of the caliper group may be expressed in steps. The first step for 0-200mm (0-8 in) calipers has an accuracy of ±0.03 mm (±.0012 in) in most instances and will become less accurate by ±0.01 mm (±.0004 in) for each additional 200 mm thereafter. For example, by the time it reaches 0-400 mm (0-16 in), the cumulative accuracy will be ±0.04 mm (±.0016 in). This will continue all the way up to 1000 mm.

This increase of inaccuracy can be avoided, however, when a set of gauge blocks is inserted to check the caliper at certain values such as 150 mm, as shown in the above example. By checking against this length standard, this caliper is no longer off by 0.03 mm plus or minus. It reads exactly 150.00 at 150 mm.

For longer sizes, choose standard bars supplied with micrometers if long gauge blocks are not readily available. Have the bar calibrated to make certain that it is traceable and its size certified. If it is too difficult to do in-house because of the long size, send it to an A2LA (American Association for Laboratory Accreditation) registered calibration house. For example, a 300 mm long standard bar will be accurate within ±0.007 mm (±.00025 in for 12 in bar), which is accurate enough to calibrate any 300 mm caliper.

Chapter 12 Indicators

"THE KEY PART OF A COMPLETE MEASUREMENT SYSTEM"

Dial indicators *(a)* and test indicators *(b)* represent yet another important category most commonly known as analogue gauges. They are effective in checking circular runout or transferring the height from stacked gauge blocks to unknown heights on a granite plate.

The dial hand movement is based on a series of rack-and-pinion and then gear-to-gear magnifications. Due to this construction based on gears, indicators are susceptible to "back-rush", which affects the gear train when the hand reverses its direction.

Most commonly, the indicating accuracy is ±1 µm to ±2 µm (±.00005 to ±.0001 in) but 0.01 mm and .001 inch long-range reading indicators are most popular. Beyond this threshold, in higher resolution models, the gear train will no longer be used, and another system called LVDT will take over which goes all the way to 25 nm (.000001 in) in resolution.

AGD specified Series 2 Dial Indicator

Dial and test indictors require three additional items to complete the package: (1) length standards such as gauge blocks, (2) datum plane represented by granite surface plate, and (3) a transfer stand to hold sensitive indicators vibration free. Only a very narrow indicator range will be used in this comparison of known (gauge blocks) against unknown.

Colour coded (Yellow – US Only)
Metric Test Indicator

Bench Comparators

This design comes from the early period when a rack-and-pinion was not used in the indicator. A fine chain was wrapped around the shaft instead and its diameter dictated the fate of magnification. There must have been a thriving industry in New England where these gauges in large quantity were used in production. A 5-digit serial number engraved is a testimony to the popularity of this bench comparator.

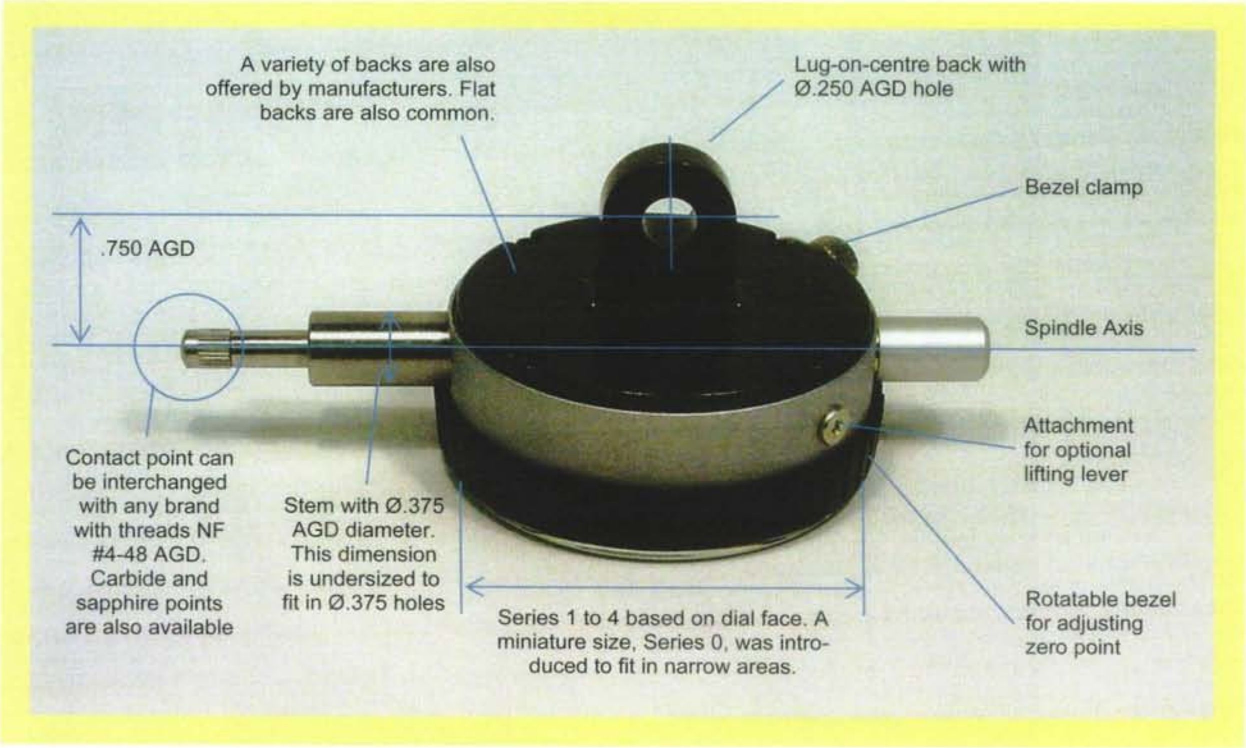
- *(a)* A knob to pull the entire spindle upward to allow workpieces to come directly under the contact point.
- *(b)* Zero-adjust. By this knob, the indicating hand could be set to the 12 o'clock position without moving the contact point.
- *(c)* 5-digit serial number.
- *(d)* Upright post could be vertically adjusted to accommodate various sizes.
- *(e)* Anvil could be flat, domed, or any other form and was secured from the bottom.

Mitutoyo Museum, Suga Collection
Circa 1883

When the dial indicator was first put into use, it took the form of a bench comparator. Invented by John Logan of Waltham, MA, his invention was to cope with a rising demand to measure workpieces more precisely. He also received several more patents on dial indicators later. The pointed tip of his indicator (see above) suggests that this particular bench comparator was used to measure narrow grooves or small parts. The point is only about Ø1 mm (.040 in) and 5 mm long (.200 in).

From this earliest example, it is clear that the indicator by itself cannot measure anything unless at least two other elements are present: One of which is a flat surface *(e)*, and the other is a holder to firmly hold the indicator, as seen in this example *(d)*, which is vertically adjustable to accommodate various sizes. It is unreasonable to expect that such an old gauge can be up to today's standards more than a century later, but it was nevertheless tested in the spirit of scientific curiosity. The comparators' range is .200 in, resolution .001 in; when the gauge was calibrated against .150 and .170 in gauge blocks, it was observed that the readings were very slightly over by less than one-half of one graduation. This could be owing to the fact that one inch during the 1880s could have been slightly different. As a point of note, gauge blocks were only invented twenty years later in Sweden.

American Gauge Design Specifications



A variety of backs are also offered by manufacturers. Flat backs are also common.

Lug-on-centre back with Ø.250 AGD hole

Bezel clamp

Attachment for optional lifting lever

Contact point can be interchanged with any brand with threads NF #4-48 AGD. Carbide and sapphire points are also available

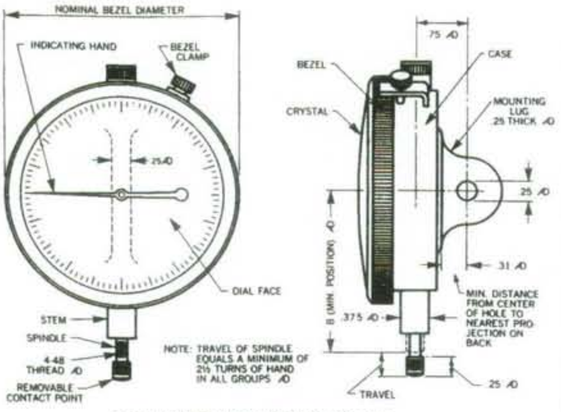
Stem with Ø.375 AGD diameter. This dimension is undersized to fit in Ø.375 holes

Series 1 to 4 based on dial face. A miniature size, Series 0, was introduced to fit in narrow areas.

Rotatable bezel for adjusting zero point

In 1945, all major dial indicator manufacturers gathered in New York City and worked on the landmark specification that encouraged greater interchangeability amongst brands. This standard was called AGD for American Gauge Design. Nearly 50 years later, AGD still is the backbone standard of all indicators used in the United States.

AGD standards specified only inch models then and when metric came later, those metric models in the U.S. followed the path of AGD specifications. The stem diameter *(a)*, for instance, which was set at Ø.375 in by AGD also became the standard diameter for metric models as well. This was opposed to the ISO specification for the same stem which is Ø8 mm, and thus smaller than Ø.375 in. Therefore ISO metric models require a split collar to adapt the Ø8 mm stem into inch fixtures.

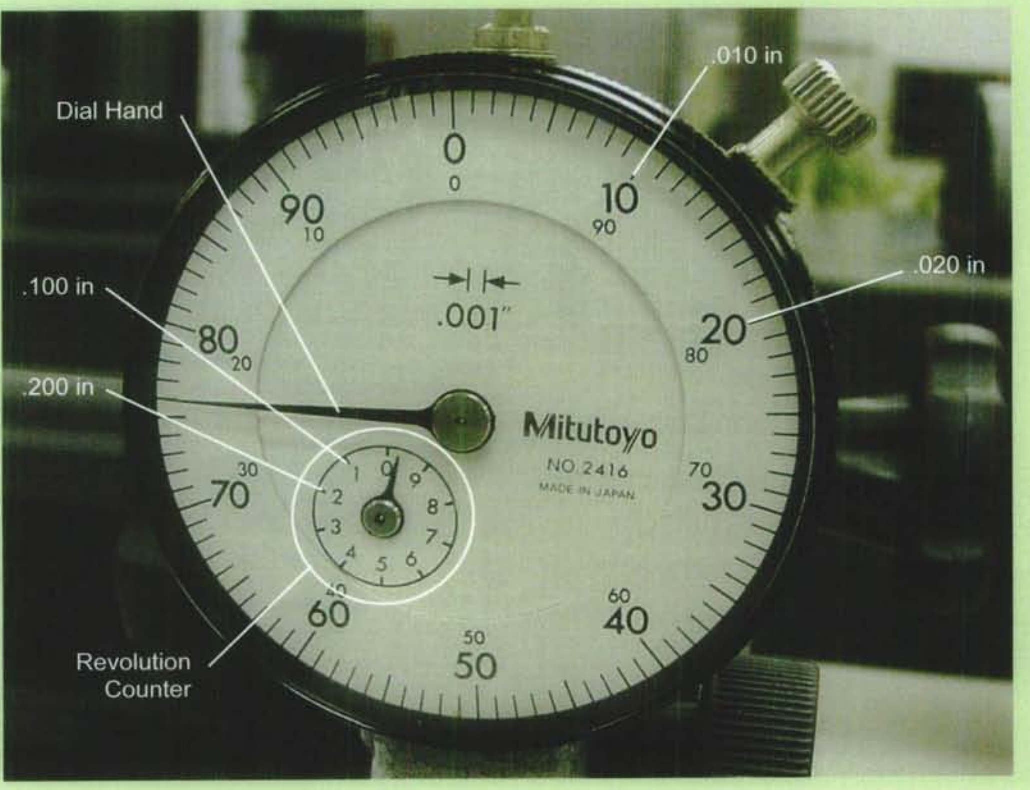


AD means American Gage Design Specification.

The original AGD specified in 1945

Another significant difference between the AGD metric and the ISO metric is the face colour. All AGD metric dial faces are yellow to differentiate them from the white inch models at a glance. This colour-coded dial face system is effective on the shop floor, with the phrase "Yellow dial face means metric" now widely understood in the US. Similarly, metric dial calipers are also featured with yellow dial faces, as are test indicators. Again, this practice is limited only to the inch/metric bilingual USA.

Dial Indicators



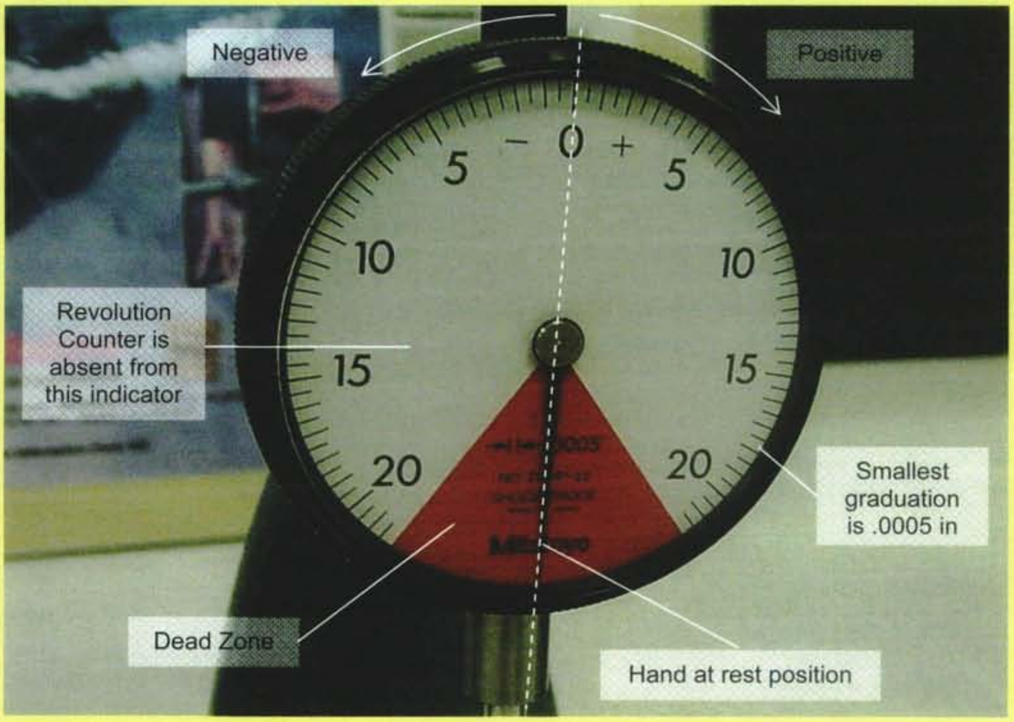
A long range, 1-inch travel dial indicator with a continuous dial face

This model is a typical inch dial indicator having a "continuous" dial face from 0 to 100 divisions in the clockwise direction. There are 2 hands on the indicator: The larger one is the dial hand, and the smaller one is called the revolution counter. When the dial hand makes one complete revolution, it indicates 100 units, that is, .100 in. As the dial hand begins on its next revolution, the revolution counter will advance counter-clockwise by 1, indicating the number of revolutions, each worth .100 in, hence its name. Over the whole 0 to 1 inch range, the long hand will rotate a total of 10 times, and the smaller hand will complete one full revolution.

All numbers on the dial face shall be marked in the unit of thousandths of an inch (i.e. number 10 means .010 in and 5 means .005 in). This is one of the AGD specifications, which the ISO standard disagrees with.

Note that when the spindle is fully extended and at rest, the long hand on the dial points to the 9 o'clock position, in accordance with the original AGD standards. ISO-compliant indicators are different: Their hands point to the 11 o'clock position instead under the same conditions.

Metric indicators for the U.S. market are featured with yellow dial faces (colour-coded) to meet ASME B89 standards. White metric dial faces, if found, are from Europe or Japan produced to meet ISO specifications. Colour-coding dial faces is an American solution since inch and metric will coexist for many years to come: An example is the dominance of the inch in the aircraft industry and metric in the automotive industry.



A one-revolution dial indicator with a balanced dial face and dead zone. This indicator is ideal for measuring size tolerance up to ±.020 in.

The dial indicators with a balanced dial face are primarily for comparison measurements, requiring a master or standard such as gauge blocks to zero-set the indicator. In this comparison method, the stand, clamp, table, and everything else in the measurement circle plays a critical role.

This model is known as a "One Revolution" model. As its name implies, the dial hand makes only one revolution, where normally it does two and a half. The special arrangement completely eliminates the need for a revolution counter, and makes it nearly impossible to read the dial wrong. The intent of the unconventional design was to eliminate potential reading errors. A so-called "dead zone" was added for this reason. The indicating hand indicates a valid value for less than one revolution in this example.

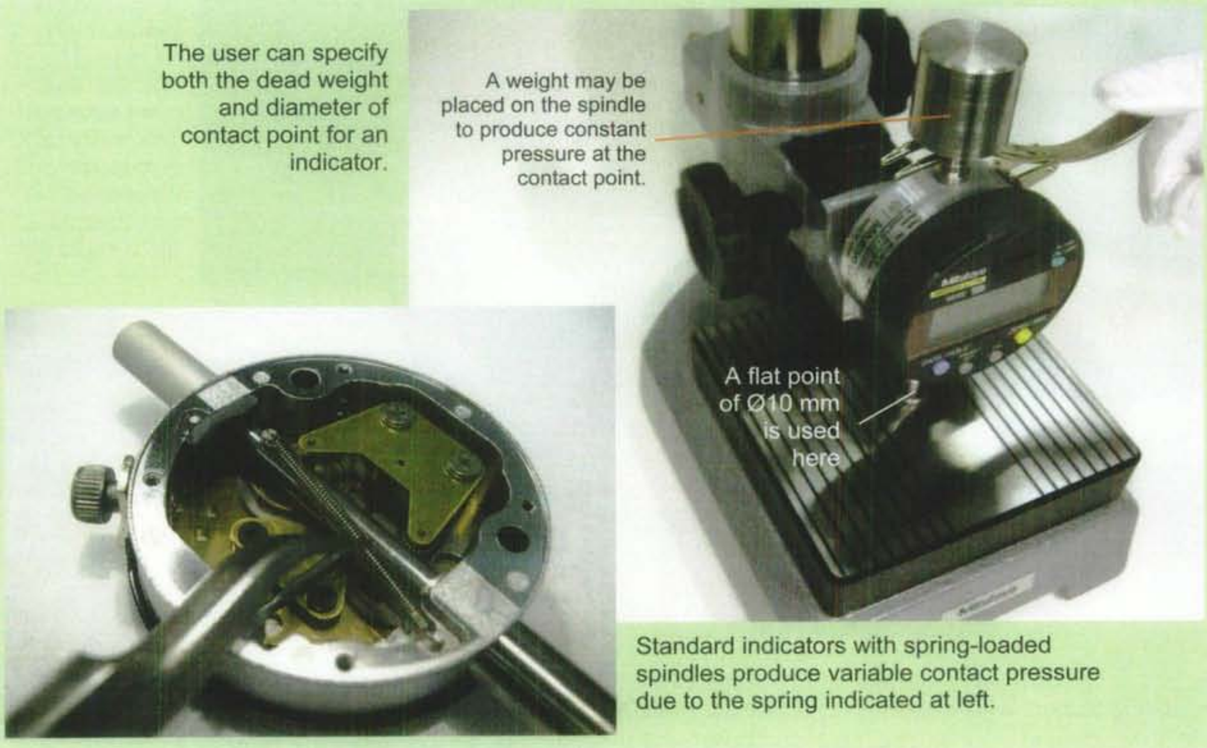
Unlike other AGD specified indicators, where the hand is supposed to rest at 9 o'clock position, this model's hand stays within the dead zone when it is not activated.

The contact points on all indicators are entirely interchangeable from brand A to B to C to D, so long as they are inch models. The same holds true for yellow colour-coded AGD metric indicators. ISO contact points use M2.5 threads and are interchangeable with all other ISO specified contact points. They are normally made of hardened steel having a round or ball point. A wider variety of points are also available: Depending upon the geometry of the workpiece, if the standard ball point seems inappropriate, it can readily be interchanged with flat, knife-edge, needle, or roller (for continuously moving features) type point. For abrasive materials, use a carbide or sapphire point.

Indicators can be used horizontally, but cannot be used upside-down. This is because the preloaded spindle is not strong enough to overcome the combined weight of the spindle and gear train. Analogue gauges such as this indicator will be best used in large-scale production runs.

Pressure at the Contact Point

The user can specify both the dead weight and diameter of contact point for an indicator.



A weight may be placed on the spindle to produce constant pressure at the contact point.

A flat point of Ø10 mm is used here

Standard indicators with spring-loaded spindles produce variable contact pressure due to the spring indicated at left.

All indicators, analogue or digital, employ a spring to preload the contact point during normal operation. The pressure of contact varies, as the below table indicates, from 0.6N to 1.4N in a linear progression (example: 0-1 in model). The initial pressure is light but it grows proportionally heavier, as the spring is stretched when the spindle is extended.

Interchangeable Contact Points for Dial Indicators

Depending on the workpiece to be measured, the contact point on a standard dial indicator can be changed simply by unscrewing it. As they conform to industry standards, finding the correct size contact point for measurement is not a problem.

By convention, inch models are supplied with NF4-48 threads. It became official in the AGD spec. in 1945. This includes metric models with yellow dial face (for USA).

Metric indicators outside the USA are supplied with ISO standard M2.5x 0.45 threads.

Many other sizes and forms are available from manufacturers.

Measuring Pressure for 0-1 in Dial Indicator	
Initial Pressure	0.6N (67 gf)
At maximum 1 inch	1.4N (143 gf)

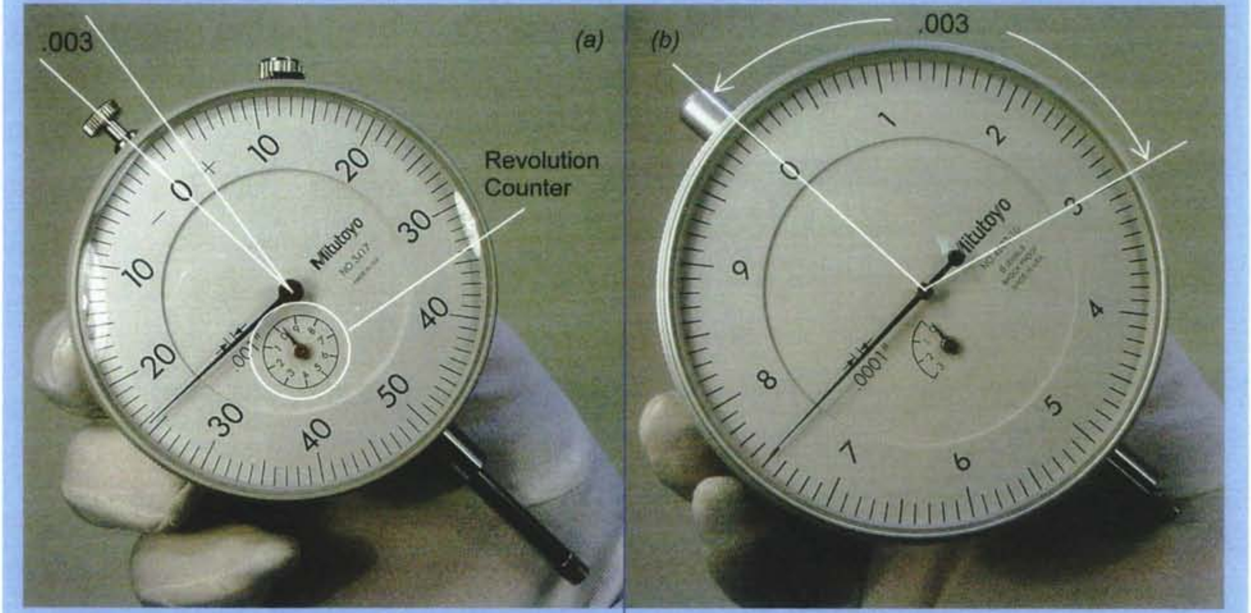
Conversion: 1N = 101.94 gf

When a constant pressure is required, this spring may be replaced by a suitable weight placed atop the spindle, as shown above. This way, regardless of where the spindle is, the pressure on the work surface remains constant. The total weight can be measured by a gram gauge placed underneath the contact point.

In this example, a flat point of Ø10 mm is incorporated. This point can be swapped with other points, due to the AGD and ISO standards (see box at left).

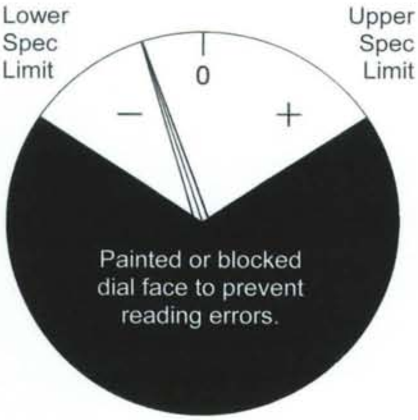
Selecting Suitable Indicators

Say you want to measure Total Runout of .003 in on a router. Which of these 2 indicators should you use?



This dial *(a)* features divisions of .001 in, with each turn of the hand covering .100 in. As a result, a change of .003 in would result in a change in only about 11° on the dial face. As a separate point of interest, the dial hand of this indicator with revolution counter rotates up to 10 times and is classified as a long-range indicator. Normal indicators, in comparison, are considered short range, turning a maximum of 2½ times.

In comparison, on this dial *(b)* above, .003 in takes up about 120° of the dial face. Under this condition, the long hand moves a great deal more, sending clear messages in real time how good or bad the Runout is. Indicators of this type, reading in .0001 in, provide clearly defined information as to where the high and low spots as the router is turned 360°.



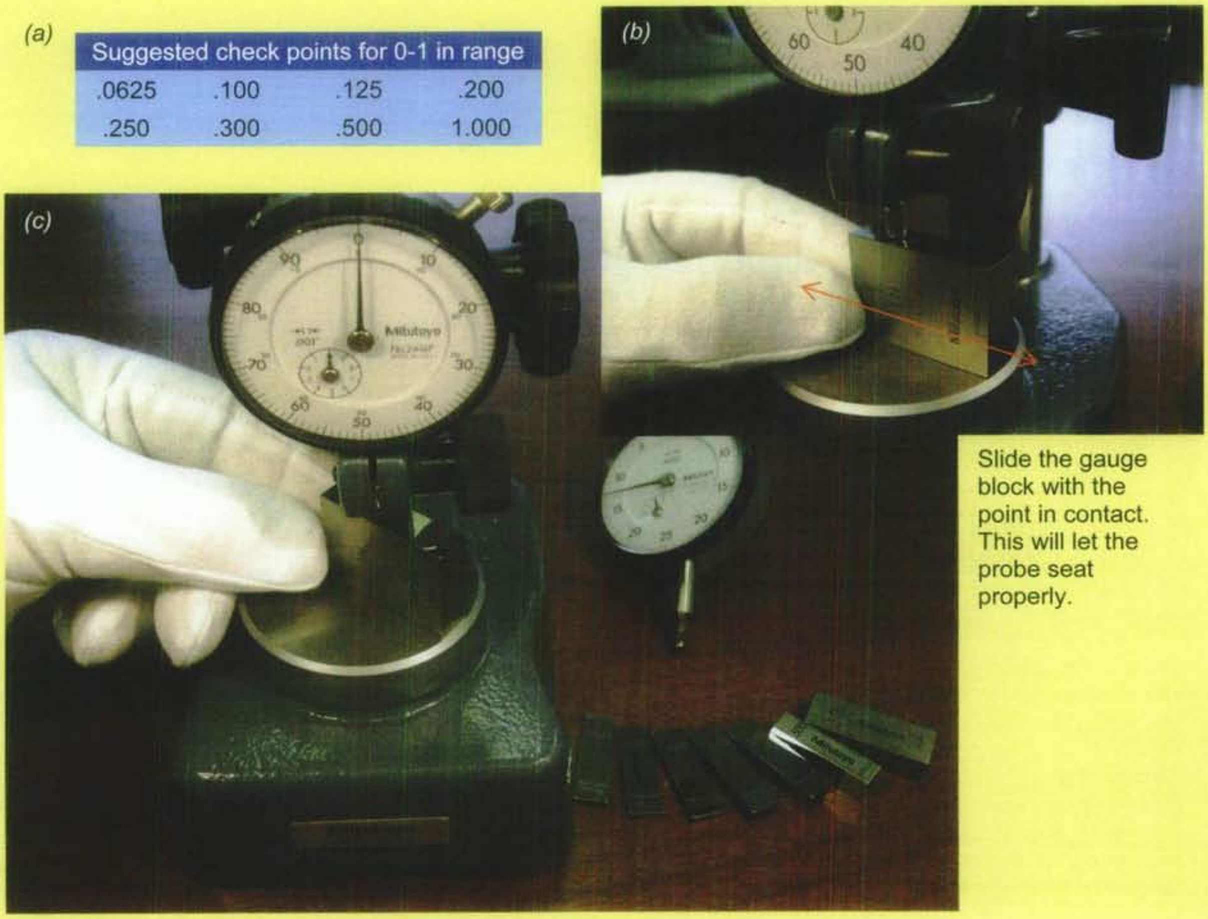
Look at the examples *(a)* and *(b)*. Given the tolerance limit is .003 in (70 µm), which one is better? If this is to check runout, definitely choose the broader spread, in this case 120° for dial *(b)*. The hand sweeping large area need not be a concern. This is exactly the purpose of this type of analogue indicator, and is what digital indicators are unable to represent.

As an alternative, the method at left, not shown in the textbook, allows operators to easily discern when Runout exceeds the specified limits. When the indicating hand isn't there, no one can read it, implying that it has exceeded the upper or lower spec limits. When it emerges into the open area the workpiece is within the upper and lower spec limits.

Indicator Calibration

(a)

Suggested check points for 0-1 in range			
.0625	.100	.125	.200
.250	.300	.500	1.000



Slide the gauge block with the point in contact. This will let the probe seat properly.

This indicator with .001 in resolution and 0-1 in range is one of the more common models in use today. As the range is the same as an equivalent micrometer, the same calibration points may also apply to this model, and are listed in table *(a)*. If the smallest value .0625 (sixteenth of an inch) is unavailable, replace it with any similarly thin gauge block. If an untested range between .500 and 1 in is unacceptable, an additional point may be used to calibrate. Generally it can be said that the check points are biased toward smaller dimensions.

This method, while simple to perform, does not take the backlash into consideration — the movement of the hand in one direction and reversal of the hand in the opposite direction — which may become a factor in runout measurements. If it must be detected, calibration equipment that incorporates an anvil moving up and down will be the answer. This is covered in more detail on page 197.

On the other hand, if the indicator is used only to measure heights or steps, this method of calibration is sufficient. Record the errors found on the dial face if any. Enter + or – 1/2 graduation. The amount of error should be less than 1 graduation in most cases.

Absolute Digital Indicators


Miniature precision glass scale behind the sliding spindle

Port to download measured data

Because rack-and-pinion is not used and with no gears in the system, both upward and downward movements not subject to a backlash error, thus making this indicator more appropriate for checking Runout.

Selectable analogue display inch/metric ±.040 in this example

Resolution: 0.001mm/.00005 in Range 0-50mm/0-2 in

The advantages of digitised gauges seem endless: inch/metric conversion, convenience of up or downloading the measured data into other systems, no reading errors, etc. However, there may be a minor drawback: Because it is "virtual", a set zero will only exist until it is switched off. Unlike analogue gauges, where the zero point is basically permanent, in the world of digital gauges the zero origin point can be set to be anywhere within the range. Also, it can be preset to read any set of numbers entered by the operator.

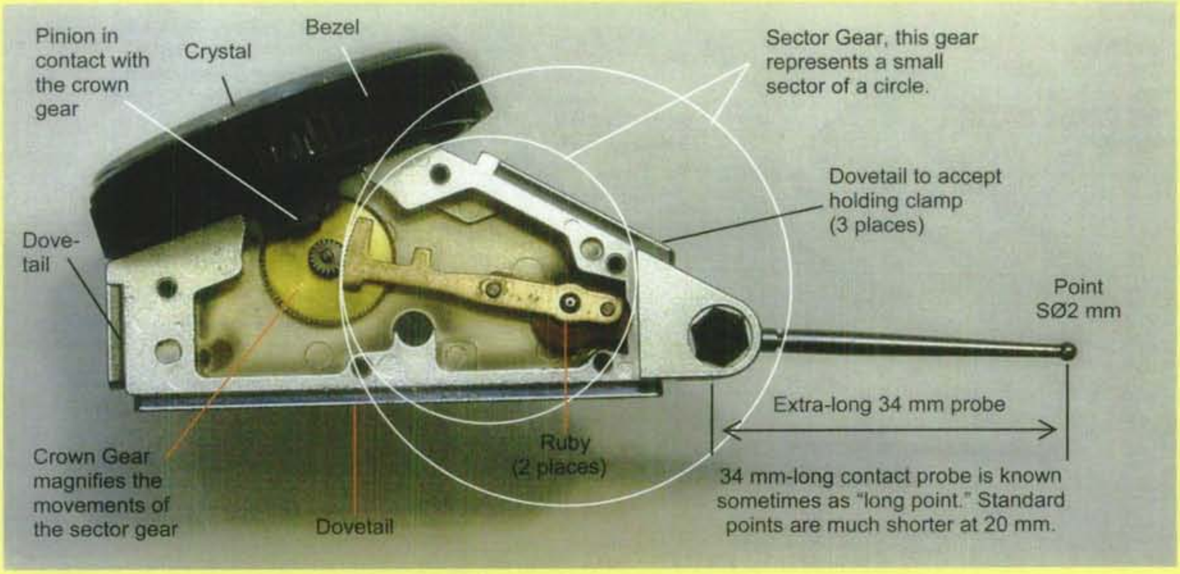
ABSOLUTE ("ABS" for short) is a feature for digital indicators where the origin point is marked with a permanent (absolute) line. For this reason, one can always check the absolute point, and if required, the reading can be switched to more common "comparison" measuring mode by a toggle switch. Zero point in comparison mode is countless, whereas the zero point under absolute mode is one.

The analogue-like feature on the LCD shown above is not as explicit or direct as the indicating hand of the dial indicators. Nevertheless, this digital/analogue gauge is useful by indicating whether the dimension measured is on the plus or minus side with respect to a standard, and by how much.

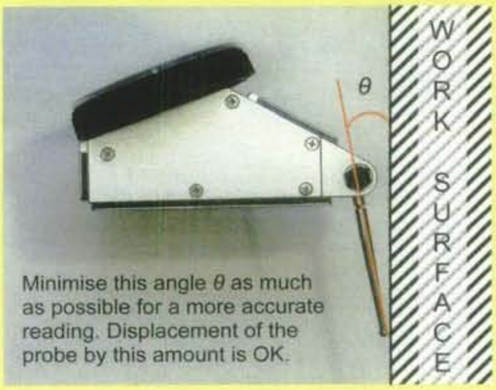
With these properties, ABS eliminates the common drawback in digital gauges, making it possible to measure from one permanent point, and giving the best of both worlds.

Digital Indicators – Inch/mm – Automation – SPC

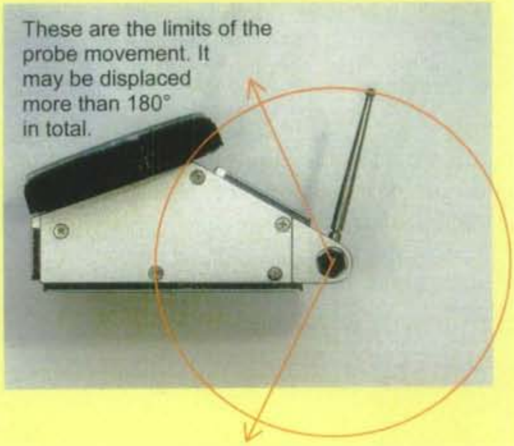
Test Indicators



34 mm-long contact probe is known sometimes as "long point." Standard points are much shorter at 20 mm.



Minimise this angle θ as much as possible for a more accurate reading. Displacement of the probe by this amount is OK.



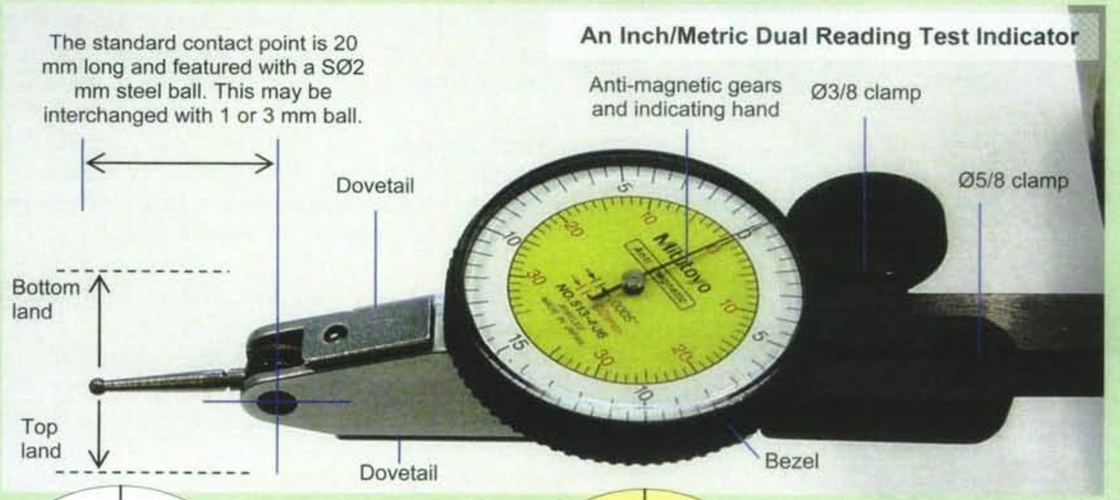
These are the limits of the probe movement. It may be displaced more than 180° in total.

As shown above, the test indicators are based on the principle of a lever magnified by a series of gear trains. This particular model features a long-probe and is used often in the horizontal position with its contact point extended. While the probe remains horizontal in most applications, it can be bent as much as 240° to check vertical work surface for example. The extra long probe is sometimes necessary to reach certain surfaces in confined areas. Unlike long-range dial indicators, test indicators are designed for comparison work in short-ranges of one revolution or less. As they are comparison gauges, a set of stacked gauge blocks or a master is required for calibration.

The test indicator shown here is known as automatic reversible type. This type reacts to the direction of pressure sensed, allowing it to measure top and bottom lands without user intervention. Other indicators are equipped with a toggle switch by which up or downward movement can be selected.

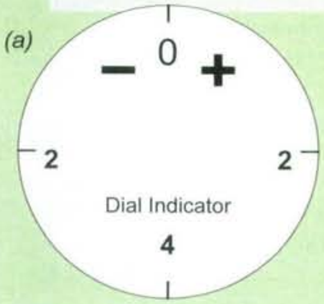
Test indicators are very sensitive gauges, and thus are damaged easily. Take care while handling the indicator, and do not drop or throw it. Handle the probe only with your hands, and do not push the probe horizontally, as it is designed for vertical movements only. For greatest accuracy, let workpieces come from behind the probe if possible (see page 192 for more details).

Dial vs. Test Indicators

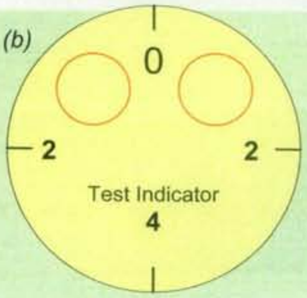


An Inch/Metric Dual Reading Test Indicator

The standard contact point is 20 mm long and featured with a SØ2 mm steel ball. This may be interchanged with 1 or 3 mm ball.



Plus/Minus symbols are always on a balanced dial face such as this one. Upward or inward movement of the contact point is "Plus" (+).



Plus/Minus symbols are omitted from test indicators to avoid reading errors.

Test Indicators conform to the AGD standard as well; yellow colour coded dial face means metric. A special case is the dual reading Test Indicator above, which is both white and yellow.

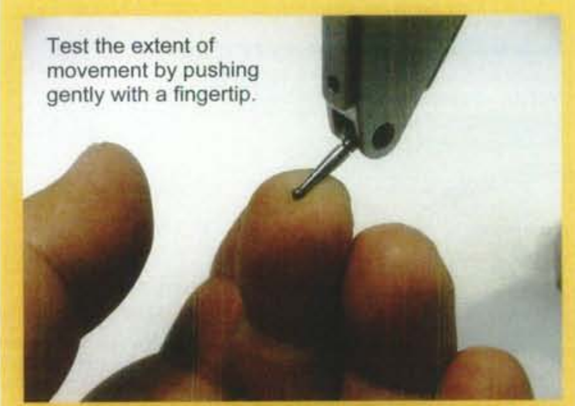
Both examples, *(a)* and *(b)*, look alike but one is marked with Plus/Minus signs while the other is without. Dial indicators *(a)* are normally used upright. Under this normal orientation, the right-hand side of the face is plus and the left is minus.

Dial Indicators are also used horizontally to check the movement of sliding tables, for example. A long-range indicator may be used to measure the movement of sliding tables or fixtures. They are also used in checking linear motion in all directions except upside-down. As the hand starts to rotate it will become clear to the operator which direction is plus and which direction is minus. If it is unclear, move the spindle manually and see which way is Plus (when the contact point goes inward, it is Plus).

On the other hand, Test Indicators *(b)*, by virtue of having contact probe horizontally extended and being able to measure top and bottom lands, cannot have +/– signs on its dial face since depending on how it is used, the indicating hand on the right side may not be plus. In order to eliminate this potential confusion caused by the presence of polarity signs, most manufactures omit them from test indicators' dial face.

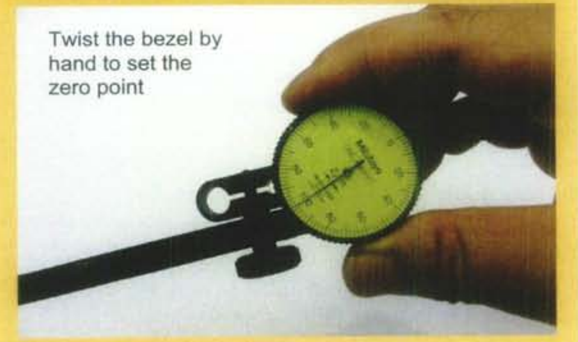
Older test indicators had a lever to change the direction of measurement up or down. Some newer models can measure either way without a switching lever. The above model is one such example. Accuracy of the indicators also depends on the fixtures and clamps used: All clamps must be tight during the comparison work. Cosine error is also a factor, and is explained on page 193.

How to Use Test Indicators



Test the extent of movement by pushing gently with a fingertip.

Move the probe gently



Twist the bezel by hand to set the zero point

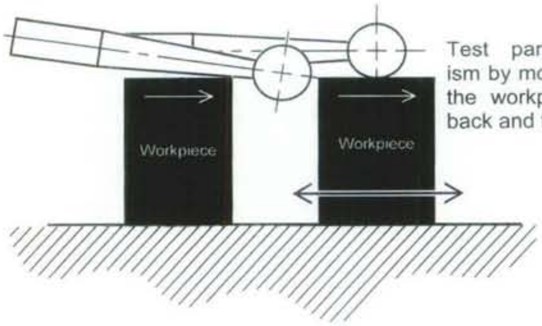
Tighten the knobs and clamps before measurement.

Test indicators are most often used for short-range comparison work to find deviations from a standard. In order to validate actual dimensions, a reference such as master or gauge block should be present. As a rule of thumb, generally all test indicators make one revolution, and polarity signs are eliminated to avoid confusion in test indicators. Mechanical magnification is limited to 1 µm (50 µin). For dimensions smaller than this resolution, a LVDT probe must be employed (see page 198).

Artificial rubies are used to enhance sensitivities of the test indicators. The opposite end of the contact point is a pivot where pair of nuts holds the contact point only by force of friction: The contact point is designed to be interchanged.

Never use pliers to move the probe. The contact point must be gently pushed by fingertip as shown at left. The contact point can be bent by as much as 240° in total.

Bring in and slide the workpiece from back to front whenever possible as shown here. The probe will be gently lifted in the process. When this is done the other way around, sudden upward movement may affect the gear train and may cause damage.

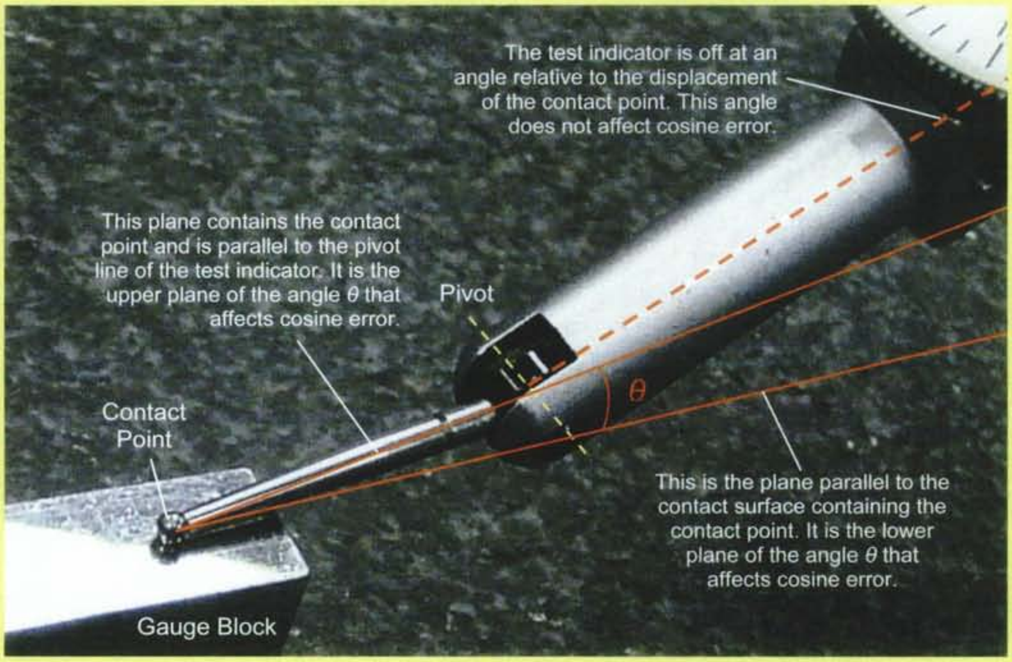


Test parallelism by moving the workpiece back and forth

Also move the part under the contact point in and out to check if the top land is parallel to the reference plane (granite table). It is also a good idea to move the transfer stand instead to check parallelism. If the workpiece happens to be a measurement standard (i.e. gauge block), the top surface should be so flat and parallel that the indicating hand will not move.

In all holding devices, at least two clamps will be required to secure sensitive indicators. Ensure that each clamp or knob is tight before commencing measurement.

Test Indicator Cosine Error



The test indicator is off at an angle relative to the displacement of the contact point. This angle does not affect cosine error.

This plane contains the contact point and is parallel to the pivot line of the test indicator. It is the upper plane of the angle θ that affects cosine error.

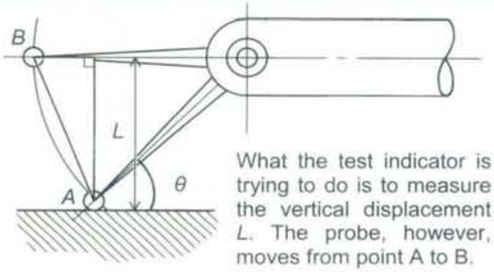
This is the plane parallel to the contact surface containing the contact point. It is the lower plane of the angle θ that affects cosine error.

The angle θ that affects cosine error is the angle between the two planes passing through the contact point, as illustrated at left. It should be as small as possible for most accurate results.

Because the test indicators' magnification system is based on a lever making circular motions about a pivot-point, it must be noted that they are subject to a cosine error as illustrated here (at right). The goal of the contact point is to measure vertical distance *L* by moving straight up and down, but in actuality traces through an arc. As a result, the values read may be larger than the actual distance, and it is noted that the displacement is proportional to the amount of error. Therefore by keeping the theta θ as low as possible, as shown in the examples *(a)* and *(b)*, cosine errors may be considered negligible and be disregarded. As a rule of thumb, this value should be preferably less than 15°.

If the indicators are used for comparison work, by having a master or gauge block as a reference and a low contact point angle, cosine error can be dismissed. A check that can be done to verify this after zero point is set is to measure a known thin gauge block such as 0.5 mm or .050 in. Check if this dimensional increase is correctly reflected or not.

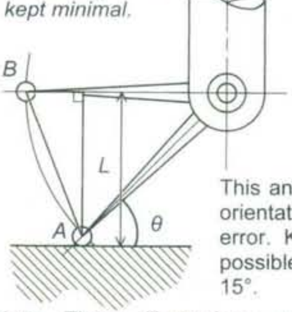
Cosine error is an inherent shortcoming due to the lever-type gauge design. The lever-type LVDT (high-end electronic comparator, introduced on page 198) is no exception to this rule. As with normal test indicators, the LVDT probe must lie as horizontal as possible to minimise cosine error.



What the test indicator is trying to do is to measure the vertical displacement *L*. The probe, however, moves from point A to B.

Test Indicator may be used in this orientation so long as the angle θ is kept minimal.

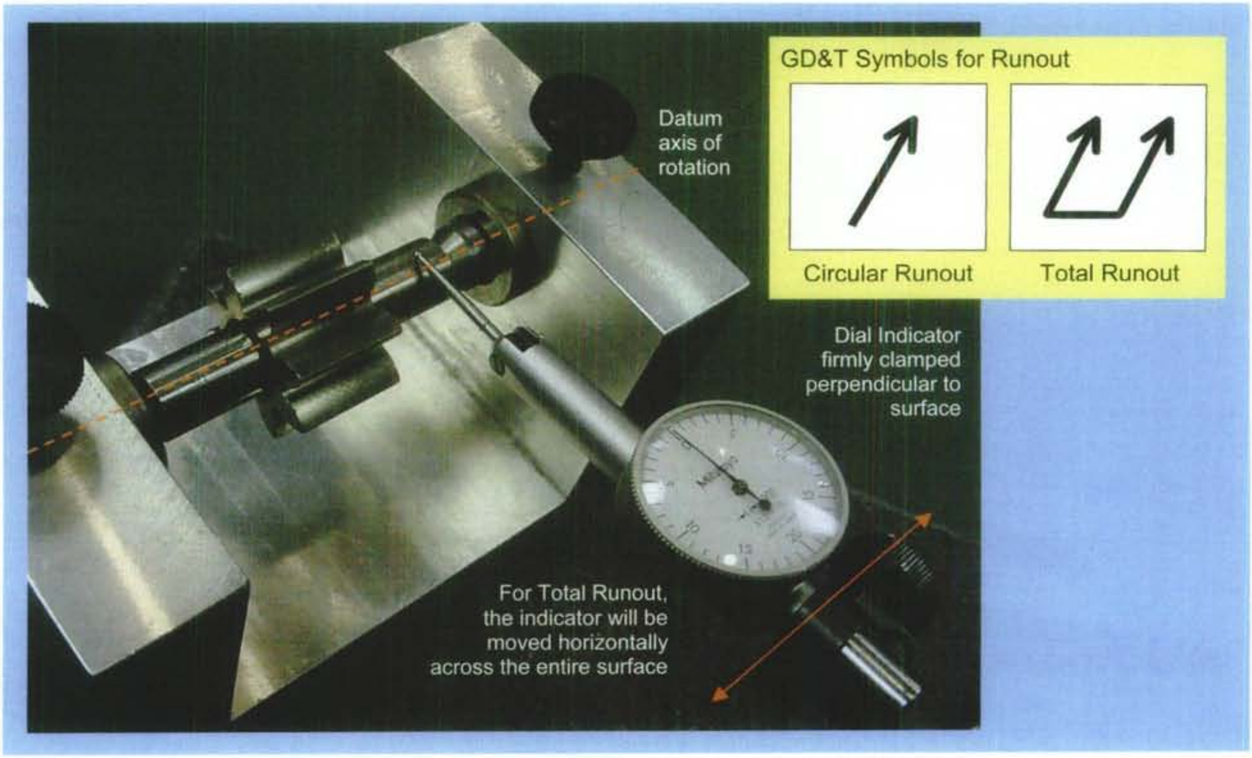
Because this arc motion will interfere with the correct reading, the moving range of test indicator is restricted to one revolution, often 1 mm total (±0.5 mm) or .040 in (±.020 in).



This angle θ in the extreme orientation produces cosine error. Keep it as small as possible, preferably below 15°.

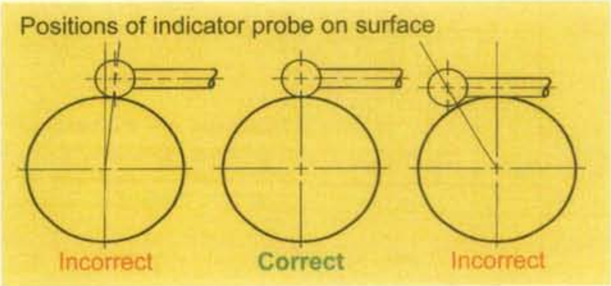
Note: These illustrations are exaggerated for explanatory purposes

Checking Runout with Test Indicators



The concept of runout is a maximum-minimum zone within one rotation from the centre. GD&T (Geometric Dimensioning & Tolerancing) standards define two types of runout: Circular and Total Runout. Both can be checked with most high-resolution dial and test indicators. If higher resolutions are needed, a LVDT probe should be used. The setup for checking runout requires a centre which represents datum axis. Often, a dead centre is preferred over a live one to avoid possible out-of-round conditions of the centre itself due to the bearings incorporated.

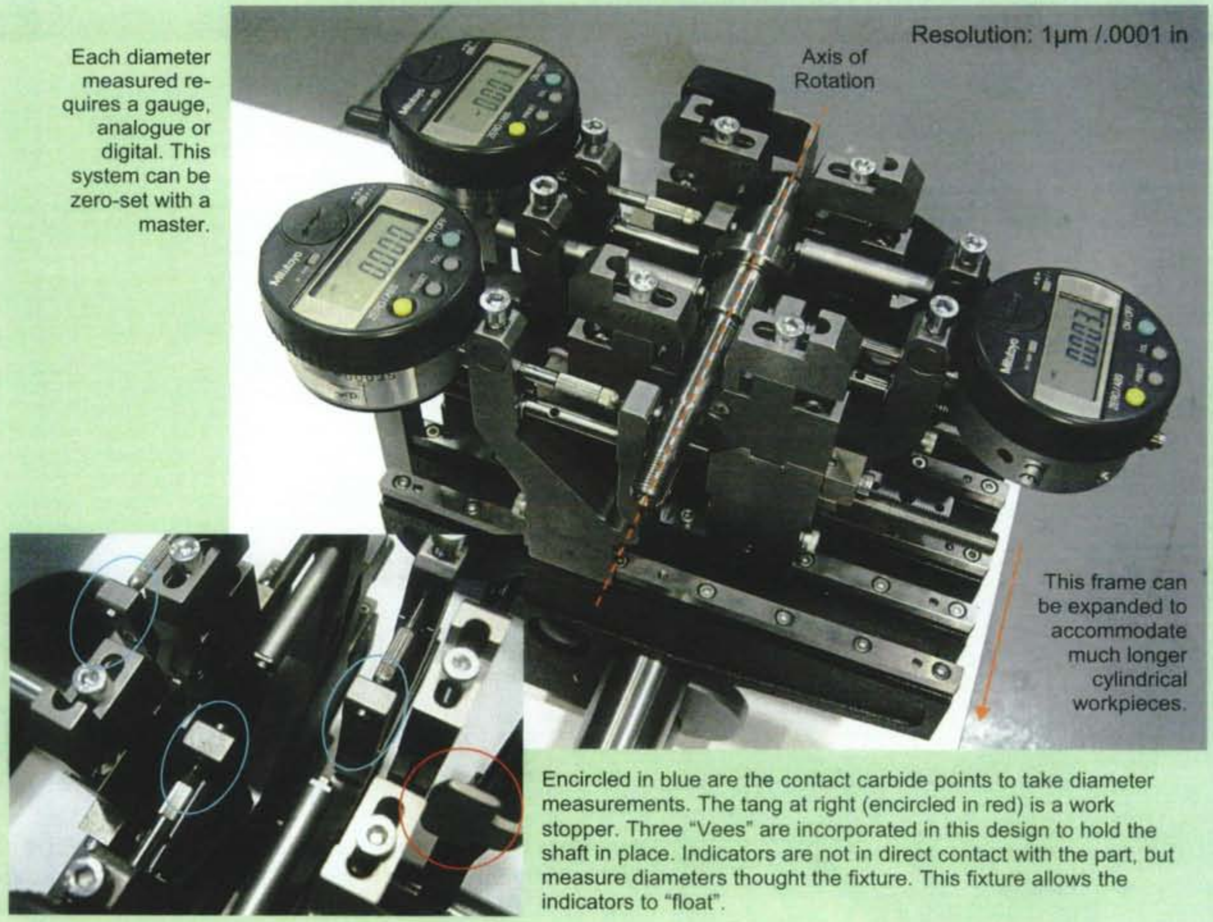
Circular runout is a sort of "spot check" to make sure the turned workpiece rotates "true." This is a series of independent runout checks anywhere on the feature specified. For total runout the gauge must touch the entire surface specified on the print. When total runout is specified, make certain that the workpiece itself is placed parallel to the surface plate, as in the above example. Total runout is stricter than the circular runout because it includes the entire surface, not just one slice.



In all cases, the cross-section touched by the indicator must remain perpendicular to the axis of rotation for cylindrical parts, including cones.

Runout specifications are usually very small. Indicators selected should have enough sensitivity to perform the job. Checking circular runout is less cumbersome than the total runout which involves the indicator sliding horizontally on a reference plane, so that the entire cylinder can be checked.

Each diameter measured requires a gauge, analogue or digital. This system can be zero-set with a master.



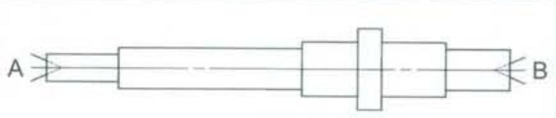
This frame can be expanded to accommodate much longer cylindrical workpieces.

Encircled in blue are the contact carbide points to take diameter measurements. The tang at right (encircled in red) is a work stopper. Three "Vees" are incorporated in this design to hold the shaft in place. Indicators are not in direct contact with the part, but measure diameters thought the fixture. This fixture allows the indicators to "float".

For any rotating shaft, as in the above example, there are always at least two issues to be concerned with: (1) diameter, (2) runout. The definition of shaft diameter is straightforward, whereas runout is a more complex concept. The shaft measured by the above system appears to exceed 10 to 1 total length to diameter ratio (i.e. If length = 10, then diameter = 1). With this ratio, runout may be specified. In this case, runout is the radial variation from the centre, in terms of maximum minus minimum. Runout has little to do with the diameter (i.e. the distance between two opposing sides): Diameter is not concerned whether or not it cuts through the centre of a shaft, whereas with runout the centre is the most important axis of measurement.

For this reason, runout specifications require the additional parameter of the limits of size for diameter. To measure that, the workpiece must be held between the centres A and B (see drawing at lower right) and the part must be rotated 360°. In this case, both cones A and B are called "simulated datum".

If a shaft rotates, and many of them do, a runout specification may be attached. Conversely, a part with a runout callout is likely to rotate. It is important to differentiate these two properties for a shaft: Every shaft must have a diameter, but runout is also an important factor not to be neglected.



To check runout, a "simulated datum" A-B may be needed.

Indicator Stands

Parallel leaf spring allows more than ±1 mm of vertical fine-adjustment.

The combination of the Indicator, Stand and Anvil form a Complete Measuring System.

Contact pressure of the indicator clamped to this stand will prop up the arm. The upright post will react to the room temperature variations.

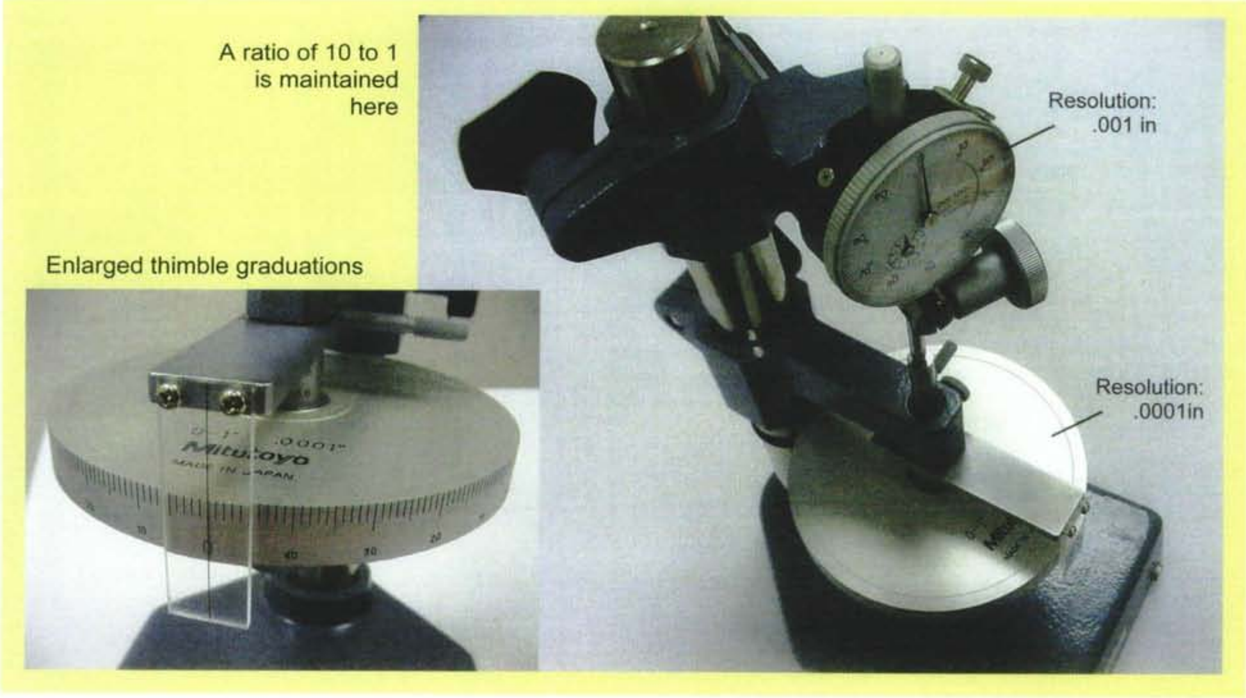
Diameter and length of the upright post L1, plus the distance L2 affect the measurements when workpieces are introduced. Contact pressure of the indicators, however small, will cause the post L1 to lean backward if it is not tightened properly.

Indicators cannot measure by themselves: An upright rigid post for support, and a reference plane, represented in this case by a flat anvil, are needed to complete the system. Therefore although indicators are a major part of the loop, it is important to realise that they alone cannot measure anything without a fixture or stand. One such stand is *(a)* above. No.1 and 3 are clamps and No.2 is the fine-adjusting knob.

Choosing a stand is as important as choosing the indicator itself: The backbone of this system, the upright post expands and contracts as room temperature changes. The longer the upright post the more susceptible to the change of temperature.

To test this, place an indicator on the stand, set it to zero against a reference plane, and come back the next day. The zero point may no longer be there due to the expansion or contraction of the post, which in turn affects the readings. This is not due to a drift of the gauge, but rather the variation of the temperature reflected by the gauge mounted on the upright post. Other posts which are small or have long diameters, such as *(b)* may also be susceptible.

Backlash in Dial and Test Indicators

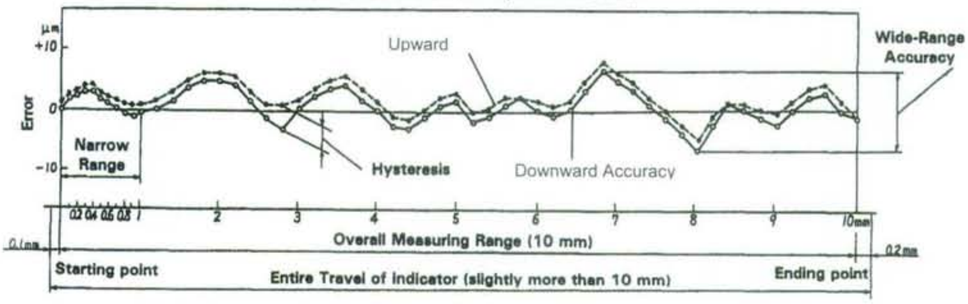


This is a continuous device to calibrate dial, test or digital indicators having 10 μm or .001 inch resolution. The micrometer incorporated in this test stand reads 10 times finer than the indicator to be tested; to 1 μm or .0001 inch accuracy. This is particularly effective in analysing gear train movements in both up and downward directions. At the end of the range, the indicator will make a U-turn without resetting to measure the backlash error. The plot of the graph will show two separate lines: one for up and another for downward movement.

Backlash error or hysteresis is an inherent characteristic of all gear-based indicators, and is due to the interaction between gears in the drive train. A certain amount of force is required before the gears will begin to rotate, and a change of direction will require some force before the indicator reading begins to reverse. As a result, two lines are plotted instead of a single line. Therefore, it is recommended to use the indicator in either up or downward direction solely.

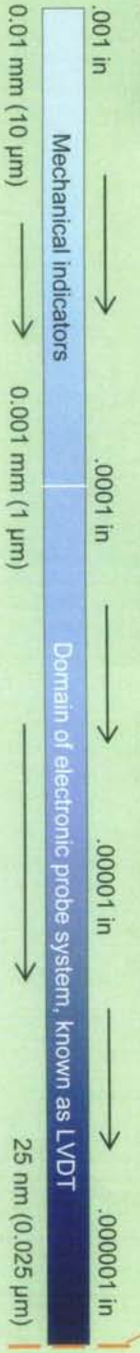
In the graph at right, peaks and valleys represent maximum error and repetitive waves are due to the rotation of gears. The two lines are separated by a zone of about 2 μm, which may be an issue depending on the accuracy required, again reiterating the need to measure in only one direction.

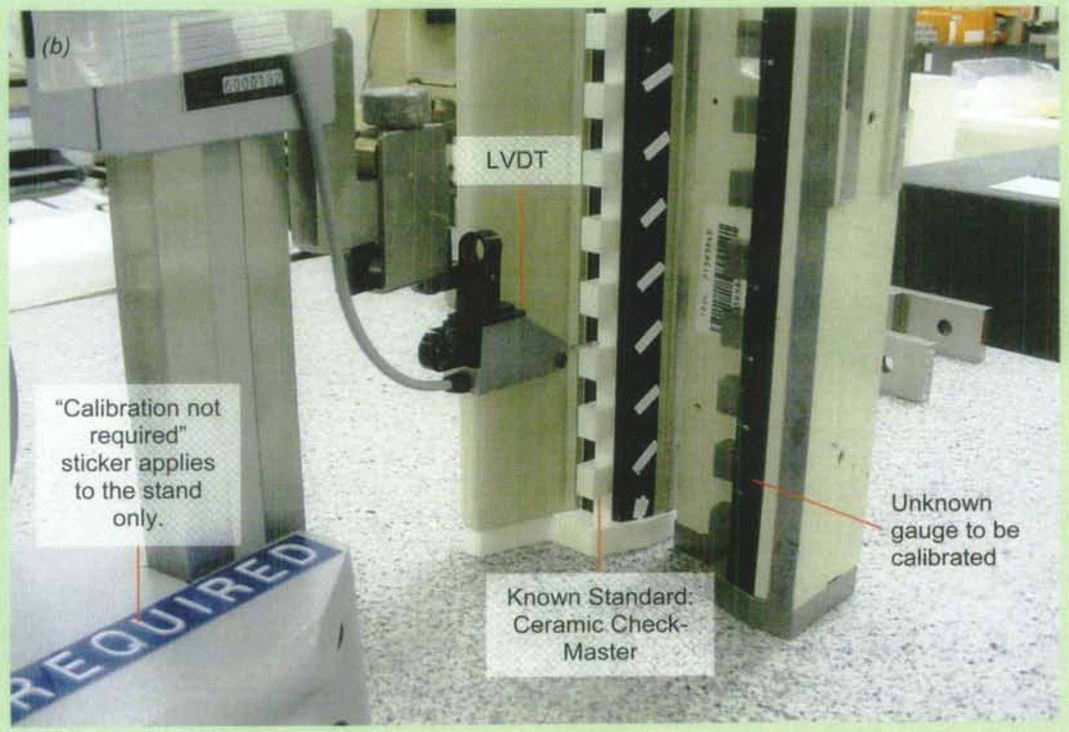
0.01 mm resolution, 0-10 mm range Dial Indicator wide-range accuracy in both inward and outward spindle deflections



Linear Variable Differential Transformer (LVDT)

(a)





As this bar from top to bottom indicates, the resolution of mechanical indicators is generally limited to 1 µm in metric or fifty millionths of an inch (50 µin). The LVDT goes beyond that to 0.1 µm or 5 µin.

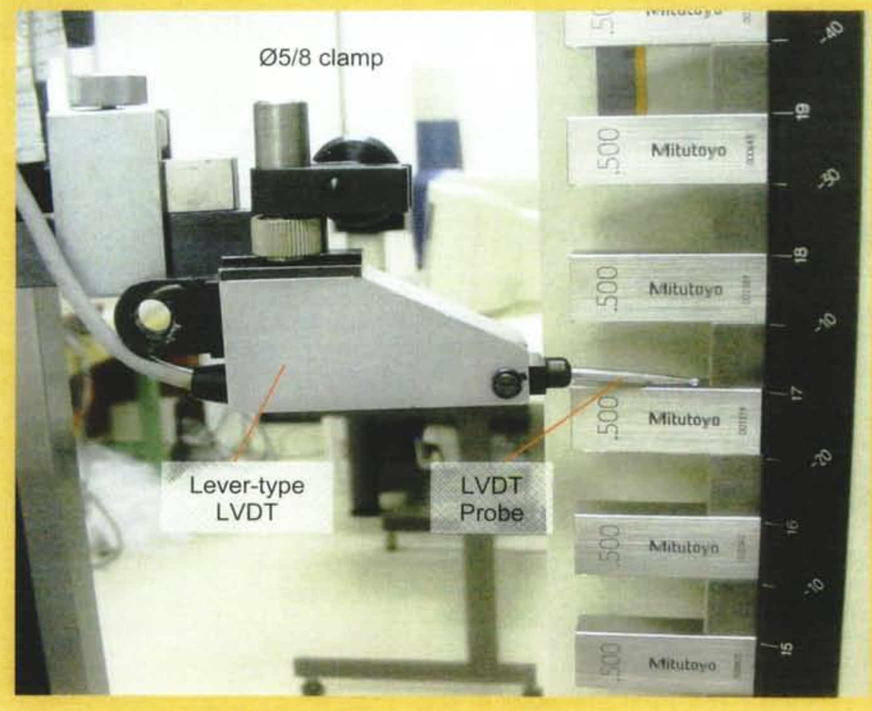
The limit of resolution of the LVDT: Surface roughness values are typically expressed at this level.

Whenever finer resolutions are required, the electronic gauge called the Linear Variable Differential Transformer (LVDT) takes over and provides resolution as small as 0.1 µm or 5 µin. At this level of magnification, one must closely observe the temperature variations and vibrations from floor or stand, both of which will influence the reading directly.

The rise and fall of temperature, called ΔT, and physical dimension are closely interrelated at this high level of magnification, leaving some to wonder which element is being measured: temperature or size. One veteran states "the most accurate person is the one with the most accurate thermometer".

The LVDT shown above is a bread-and-butter item in comparison measurements and it must be used along with gauge blocks. By making use of a high-end gauge block comparator based on LVDT, the measurement uncertainty can be somewhere in the neighbourhood of 25 nm (.000001in) to 50 nm (.000002 in) for 25 mm (1 in) and 100 mm (4 in) gauge blocks, respectively.

As illustrated in bar *(a)* at left, the smallest resolution provided by the LVDT is 25 nm (.000001 in). Dimensions below this level do not exist in the metal-working trade. In fact, units at the scale of nanometres (nm) are rarely used.



Mechanical magnifications generated by Dial and Test Indicators are usually limited to 1μm (.000050 in) level in resolution.

LVDT is based on a voltage variation as a core connected to the probe moves within a coil. The voltage variation and probes' physical displacement are linearly related to each other for a short range of about 2 mm.

Within this small range, the voltage variation derived from the physical displacement of probe is then translated into the dimensions in sub-micron level.

Measuring to 100 nanometres (0.1μm or .000004 in) and beyond is designated for LVDT. At this extreme level, a number of environmental issues must be addressed, such as temperature, vibration, heat transmitted by hand (many technicians wear gloves in calibration lab to prevent this), relative humidity, dust, etc.

Despite all those factors that might negatively affect the measurement, with some experience and practice, most operators should be able to measure 100 nm and beyond accurately: The LVDT is a system robust enough to 25 nanometres (.000001 in) in accuracy. Remember that the LVDT is mounted on a stand like other indicators, and requires the clamps to be sufficiently tightened before measurement.

The LVDT system has been a workhorse for the calibration laboratories. It is a core technology in detecting surface roughness, whose values are picked up by a diamond stylus and expressed in microns and sub-microns (or millionths of an inch).

The LVDT works on the principle that probe voltage variations and fine dimensions have a proportional relationship: the larger the displacement, the larger the voltage emitted. However, beyond a ±1 mm range this remarkable linearity disappears. Therefore, the range of an LVDT is always short; but within that short range, the LVDT provides excellent performance.

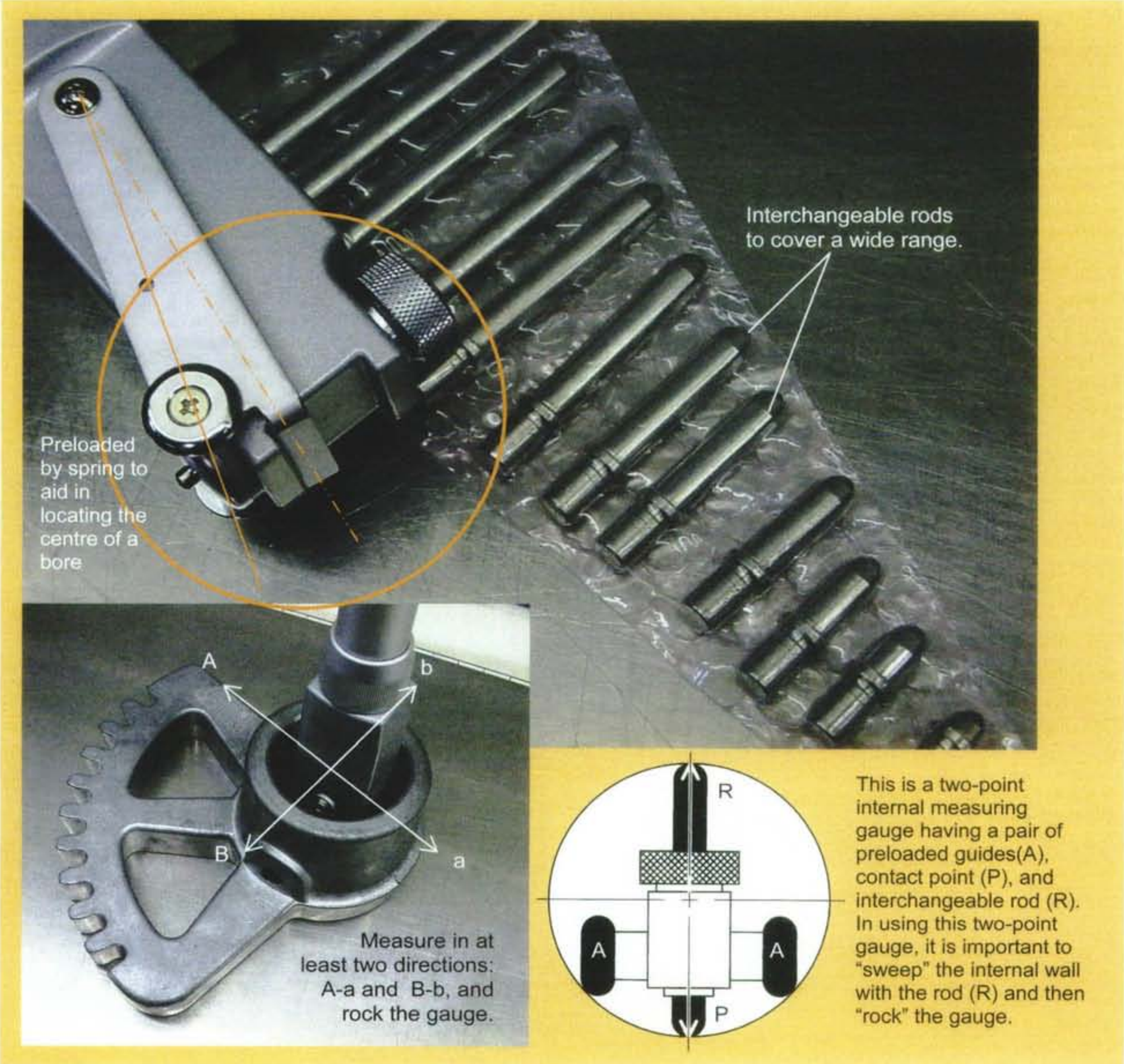
All three must be present for comparison work at micron or sub-micron level. Note that temperature variation — rise and fall of it within a short period of time — and vibrations transmitted through the floor to the granite plate may lead to poor measurement results.

Bore Size Indicators

As a rule, bore gauges must always be checked against a known ring gauge of XXX or XX class. Known means the ring gauge is traceable to a National Institute of Metrology such as NIST. To use bore gauges without a ring gauge is a very risky proposition, particularly when the parts being measured are round. At a manufacturing facility, pairs of pre-selected bore and ring gauges are supplied to the floor. The message is clear: no other choice of gauge or standards are approved. This is to stay with one authorised method, and to eliminate other methods, and thus potential errors. Unauthorised use of gauges is prohibited in this facility.

The bore gauge above features the best of two worlds: analogue and digital. The number on the LCD display is zero, meaning that the internal diameter being measured has no variation from the preset zero point.

The workpiece shown here is an unfinished sector gear: A shaft will go through this bore. A keyway may be cut in due course and the internal surface and size will be made within specifications. In measuring bores, always measure more than once by tuning the gauge 90°. Always constantly rock the gauge, and be patient in this process.



Interchangeable rods to cover a wide range.

Preloaded by spring to aid in locating the centre of a bore

Measure in at least two directions: A-a and B-b, and rock the gauge.

This is a two-point internal measuring gauge having a pair of preloaded guides(A), contact point (P), and interchangeable rod (R). In using this two-point gauge, it is important to "sweep" the internal wall with the rod (R) and then "rock" the gauge.

Throughout this Handbook, the difficulties in measuring inside diameters are emphasised. In measuring inside diameters, consider a three-point gauge as well, if this method turns out to be too sensitive. A two-point gauge is more responsive during the measuring process because it immediately reflects size variations.

The best scenario to use this gauge is to have two ring gauges made to upper and lower tolerances. If this is cost-prohibitive, select only one. This workpiece expects a mating part to come in. If such a shaft is already available, try to fit it in. A plug gauge representing the Maximum Material Condition (MMC) of the mating part will be even better. To use both ring and plug gauges would be ideal. A shortcoming of the two-point bore gauge is that it measures local sizes only one position at a time. A plug gauge will supplement the missing information

PART V

Other Measuring Instruments

PART V
OTHER MEASURING INSTRUMENTS

CHAPTER 13
PROFILE PROJECTORS

- Profile Projector Operation
- Angle Measurements
- Profile Projector Overlay Charts
- 2D Software for Profile Projectors
- Vision Systems
- Edge Detection Tools

CHAPTER 14
COORDINATE MEASURING MACHINES (CMM)

- The Cartesian (X-Y) Coordinate System
- The Polar Coordinate System
- The Touch Trigger Probe
- The Analogue Probe
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- Calibration of CMM
- Determining CMM Volumetric Accuracy
- Measuring Keyway/Keyseat
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- Measuring Threaded Holes
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- Projections and Projected Planes
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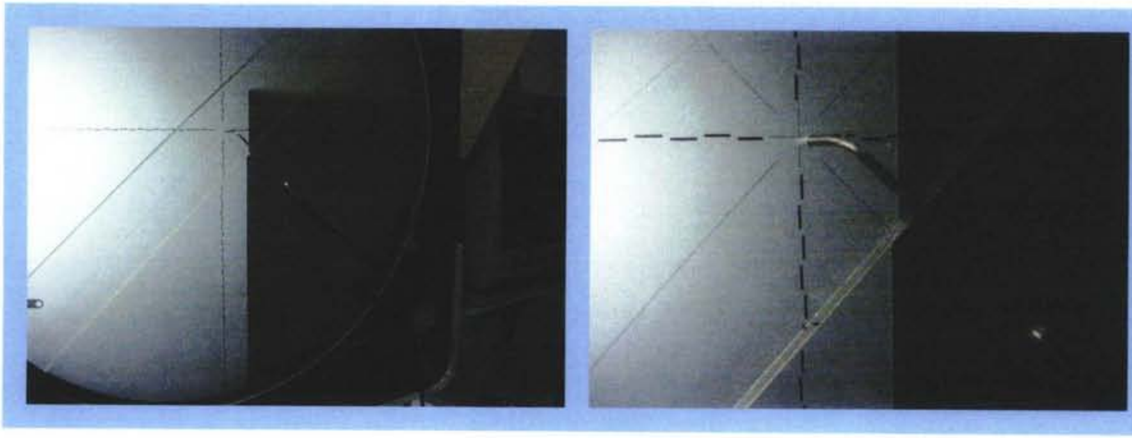
Chapter 13 Profile Projectors

"EASE BY MAGNIFICATION"

Profile projectors are powerful tools used by inspectors all over the world, ever since they were first produced years ago by Bausch & Lomb in Rochester, N.Y. The basic premise of the device is simple: To magnify an image. The historic first projector is now in the permanent collection of the American Precision Museum in Windsor, VT. Compared to today's devices, it was merely a simple shadow graph — a name still used by many today — but it worked well.

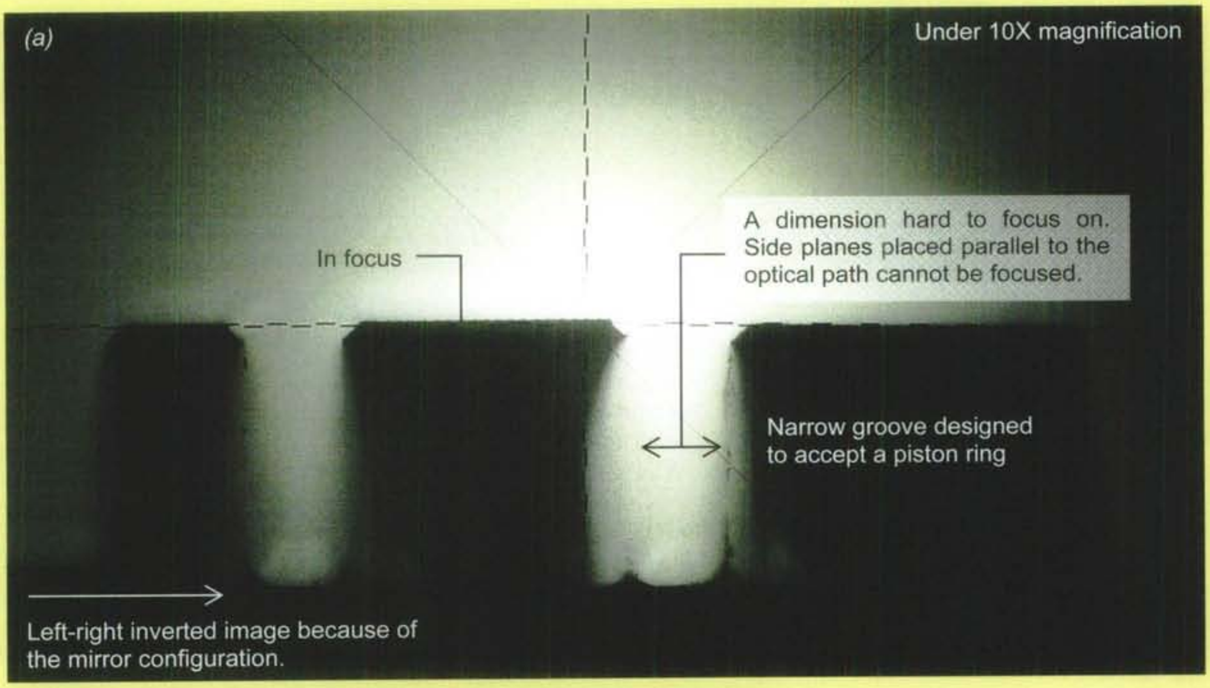
An important development was in determining the edges of images, which was achieved by trial and error in the past, and the creation of the edge detector eliminated that ambiguity. Detecting edges are now much simpler, as regardless of the direction of movement, the edge sensor can accurately detect the edge. With this device, parallax error or personal bias from one operator to another can be eliminated.


The edge detector at work on a profile projector image

An alternative to the profile projector is a more conventional lens magnification system, such as a toolmaker's microscope. Both the projector and the microscope are powerful tools with different benefits and shortcomings, but either will do the job.

Tool	Magnification
Profile Projector	5X, 10X, 20X, 50X, 100X
Toolmaker's Microscope	2X, 5X, 10X, 20X, 50X, 80X, 100X, 200X

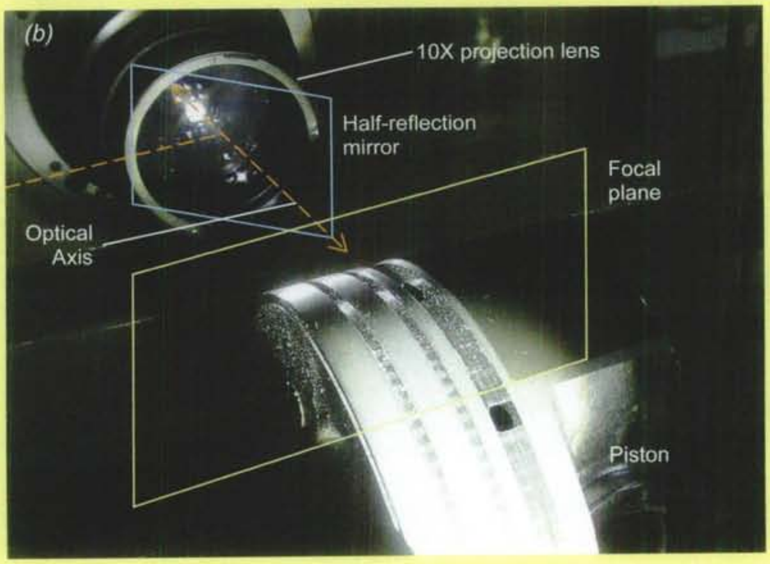
Profile Projector Operation



A dimension hard to focus on. Side planes placed parallel to the optical path cannot be focused.

Narrow groove designed to accept a piston ring

Left-right inverted image because of the mirror configuration.



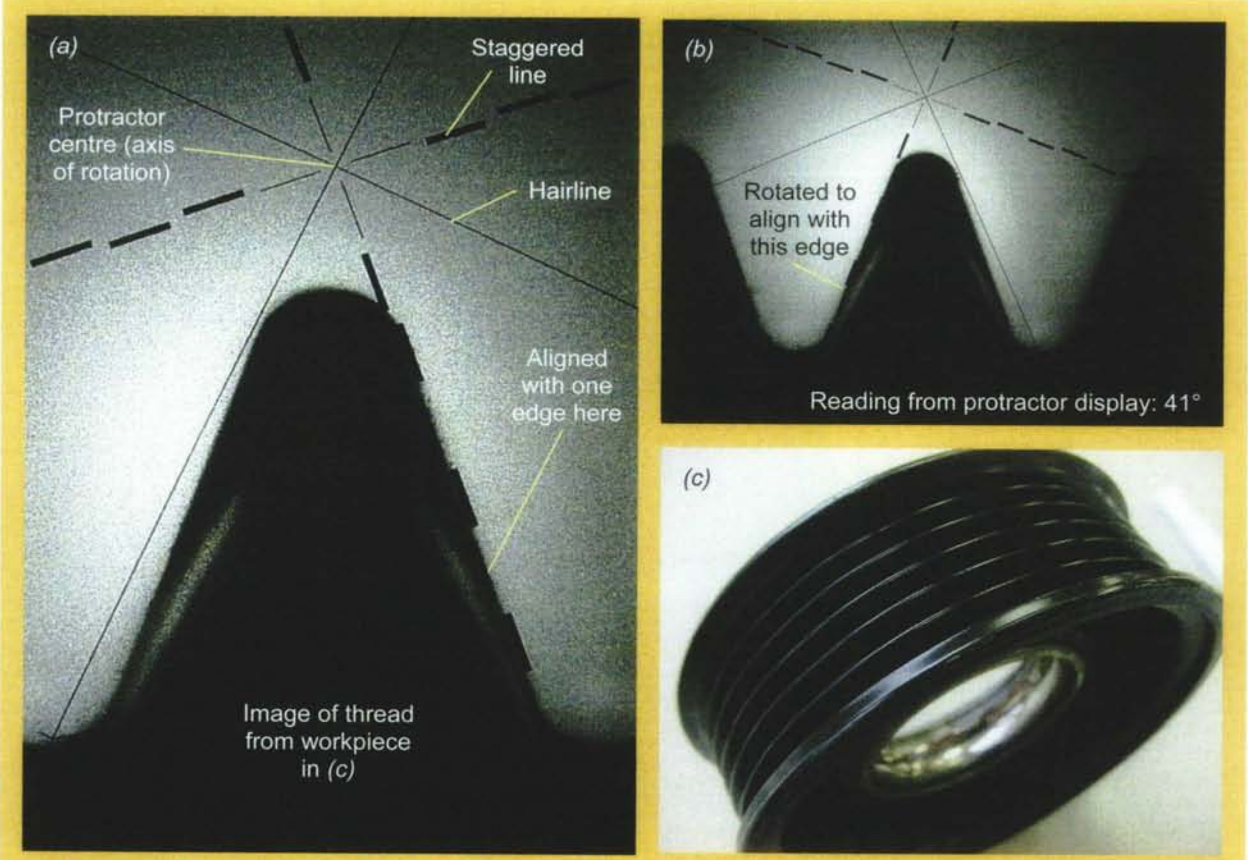
Due to the lens and mirror combination, images projected on the screen are the horizontally inverted as evident in these examples *(a)* and *(b)*.

Profile Projectors that can project so called "corrected image" use a pentagon prism to correct the image into the right orientation. However, due to high costs and loss of image clarity in implementing this approach, projectors with corrected images are hard to find.

Therefore in most projectors, when the workpiece is moved to the left, the image will move in the opposite direction. Some novice operators may be unaware of this and turn the micrometer head in reverse.

Of the entire range of lenses available, 10X and 20X lenses are the most often selected because of the brightness and clarity of details in images projected on the screen. 31.25X and 62.5X lenses are available for inch system only and the resultant image must be measured with a steel rule with a fraction scale of 16 and 32. Reason: 1/16 = .0625 in (62.5X) and 1/32 = .03125 in (31.25X). This practice is limited to the USA and limited to the very old overlays.

Angle Measurements



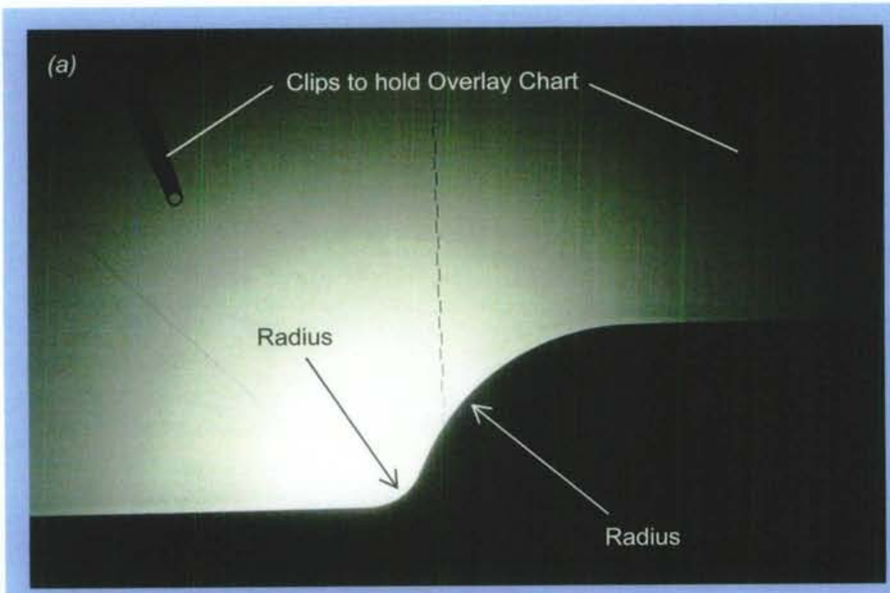
The angle of a thread measured at magnification 10X

While there are several methods used to measure angles, the easiest and most often used method is to use a profile projector. By virtue of magnification, it becomes easier to measure the angles projected on the screen to a few minutes of one degree. The example workpiece *(c)* is difficult to measure accurately using hand tools, but under 10X magnification in the profile projector, the large size makes the task easier.

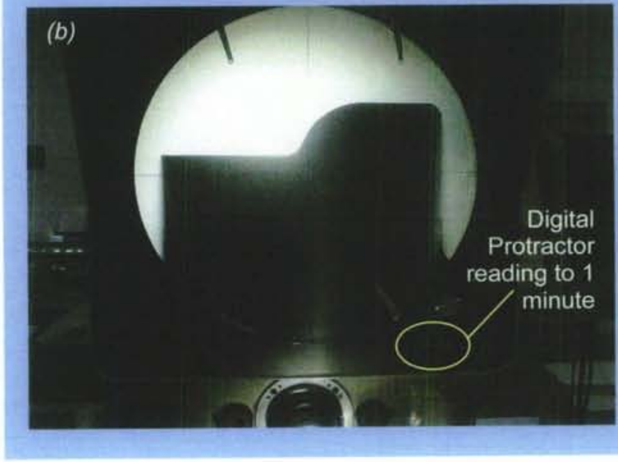
When a 20X or 50X lens is mounted, the magnification increases, but a drawback is that the screen brightness decreases. For a 50X lens the brightness is so low that projector needs to be covered to have a clear view of the image. Also, at 50X magnification edges are less defined, and are thus harder to ascertain. If 100X to 200X power is required, the toolmaker's microscope should be used instead.

On the screen above there are two types of lines: staggered and hairline. The use of either line is completely up to operator preference. To measure the angle, adjust the protractor until the line lies on one edge *(a)*, reset the counter, and then move the protractor until the line matches up with the other side of the thread *(b)*. More recent models are featured with a digital protractor that reads accurately up to 1 minute to make this process easier.

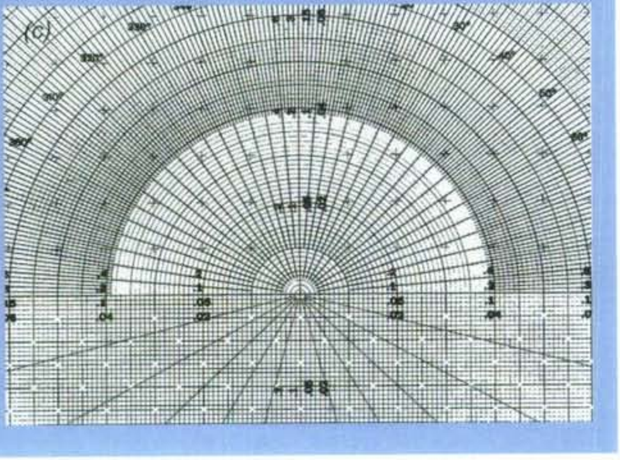
Profile Projector Overlay Charts



At 10X magnification, external radii become considerably easier to measure. If desired, an overlay chart such as *(c)* may be attached by the clips and used in conjunction with the digital protractor *(b)* to measure radii.

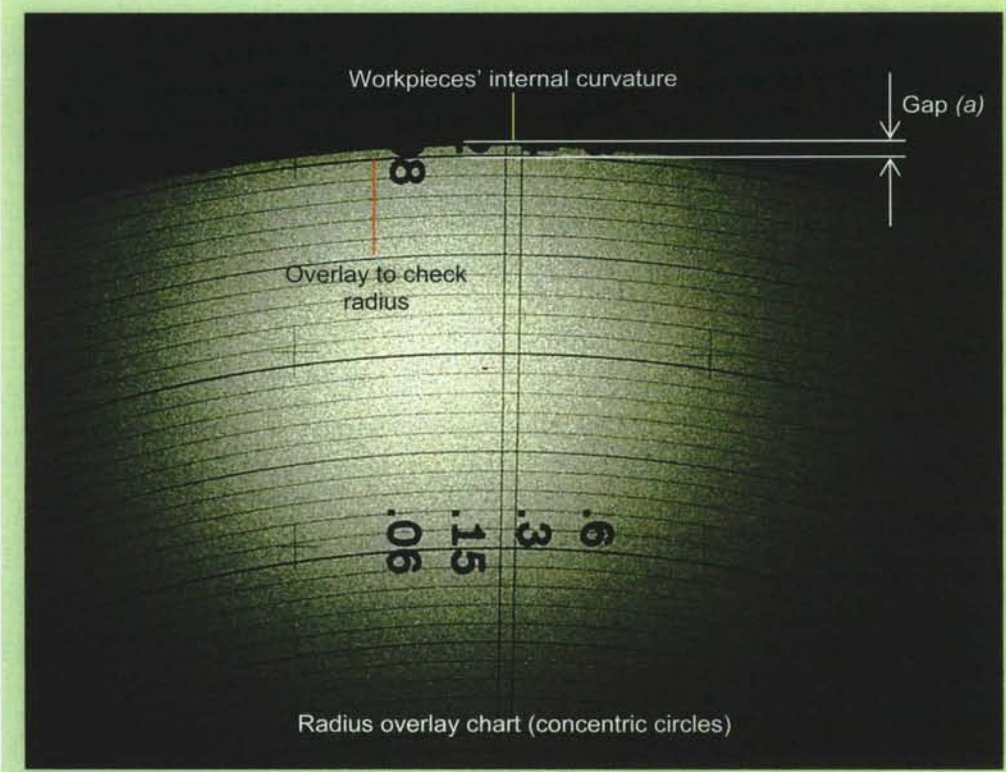


Combination overlay chart

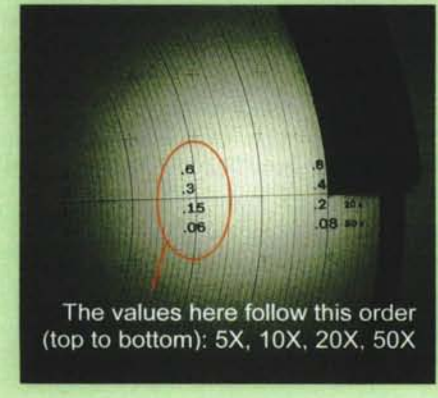


The most common applications of the profile projector are to measure radii and angle. As long as the radius to be measured is accessible, the method shown here can determine it. This image is under 10X magnification, but if larger magnification is needed, 20X or 50X lenses are also available. Larger images projected on the screen will reveal more detail at the expense of screen brightness. The overlay chart such as the one shown above right *(a)* is known by many as "Combination Chart" for general purpose because it is featured with Radius, Protractor (angle), and grid patterns.

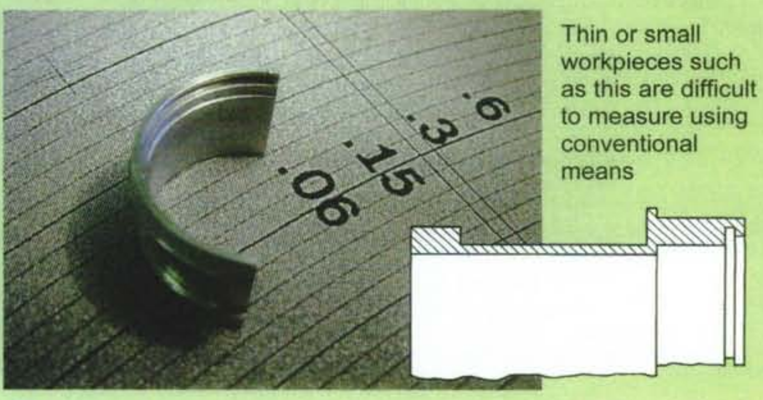
When radii are featured on the outside, as evident in this example, the measurement is simple and straightforward. When they are placed on the inside, the choices are limited. Here are suggestions: (1) dissect the workpiece in half and observe the cross-section using a profile projector, (2) use a contact method such as a CMM probe that magnifies the contour traced as much as 200X with an outstretched stylus. It traces over the work surface much like a roughness tester but with much lower magnification so that the internal form can be traced.



Out-of-roundness of a workpiece being measured at 10X magnification



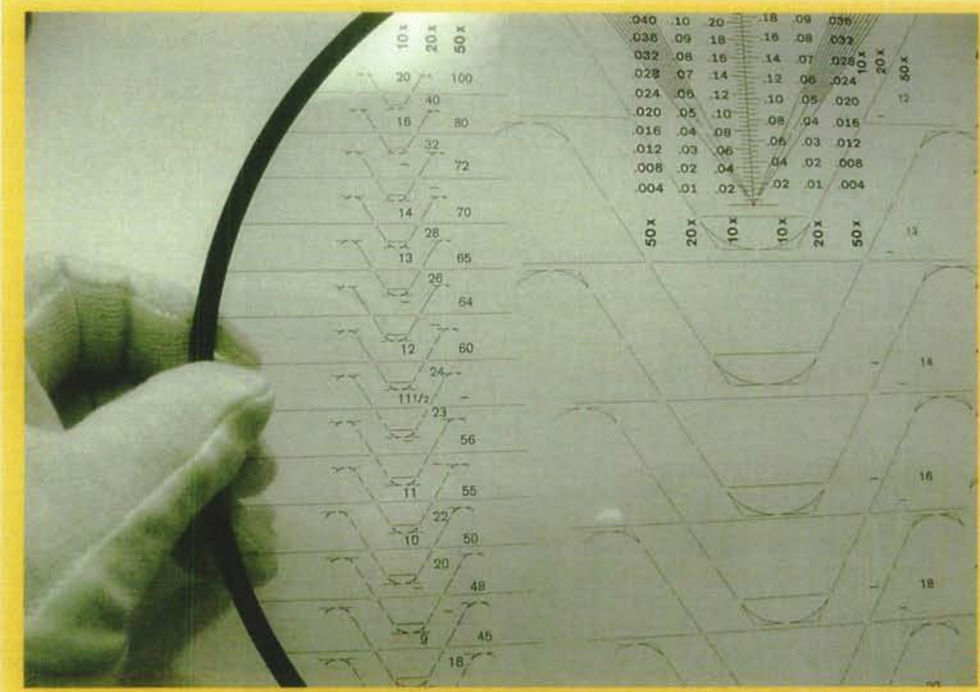
The values here follow this order (top to bottom): 5X, 10X, 20X, 50X



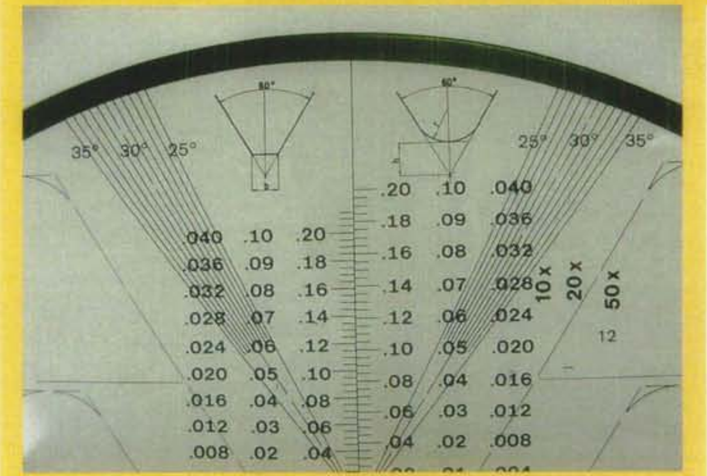
Thin or small workpieces such as this are difficult to measure using conventional means

This overlay is called radius chart: it consists of concentric circles with the dimensions for 5X, 10X, 20X and 50X indicated on the chart. To quickly find out if a part is round enough a profile projector set to 10X magnification with a radius chart clipped on the screen can provide an immediate answer. To find out the extent of out-of-roundness, the operator will read the chart or move the stage and read the amount of gap *(a)* indicated on the digital counter.

The chart is self-calibrating. Place a certified plug gauge on the stage and check if the magnification is correct. Another way to do this is to place a master glass scale on the stage, magnify it on the screen, and then measure the image projected with another glass scale. If the overlay or magnified image on the screen is never measured then magnification accuracy should not be an issue.



Screw thread overlay chart for 60 degree screw threads. This overlay accommodates 10X, 20X and 50X magnifications.



In addition to the standard overlays such as the one shown above and on the facing page, a frosted and blank Mylar may be used to draw hairlines that define upper and lower tolerance limits for a specific part under a given magnification.

Tolerance marker with upper and lower limits

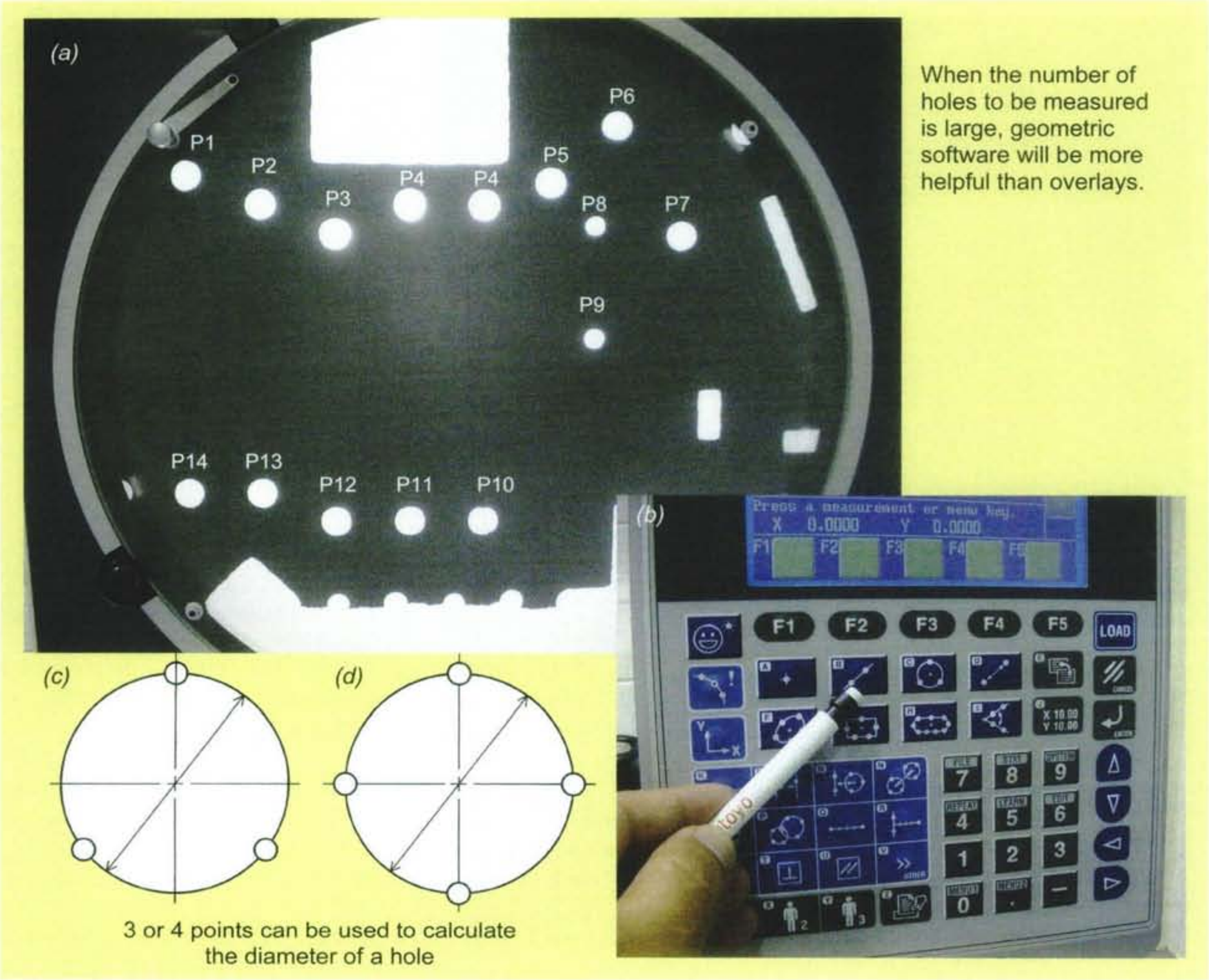
Workpiece projected on the screen is placed against the "bridge" (above) drawn by the user to see if a white gap is half-filled (i.e. between upper and lower specification limits.

One of the most frequent applications for the profile projector is to measure angles, such as the thread profile as shown above. Thread pitch can be checked as well, as the workpiece under observation is moved by a micrometer stage. Standard thread overlays for 10X, 20X, and 50X are used to measure the magnified image on the screen. Rather than use the method introduced on page 207, which is good for measuring unknown angles, these overlays can be used to check compliance of workpieces to upper and lower tolerance specifications quickly.

The commercially available overlays such as this one are composed of three layers: front, back, and the pattern sandwiched in the middle. Even if the overlay is scratched, the hairlines will remain intact. Available standard overlays are as follows:

Combination Overlay Chart (general purpose)
Screw Thread Overlay Chart (see above)
Radius Overlay Chart (see previous page)
Radius / 10° Protractor Chart (combination)
Grid / 15° Protractor Chart (combination)

2D Software for Profile Projectors



When the number of holes to be measured is large, geometric software will be more helpful than overlays.

3 or 4 points can be used to calculate the diameter of a hole

Since the image projected on the screen is always flat and two dimensional, the geometric software used is far less complex than that of a 3D CMM. All the functions of software for profile projectors can be can be contained within the single panel *(b)* shown above.

In order to operate it, individual points need to be registered on the memory chip. Once a point is memorised, the coordinate system takes over with respect to the X-Y origin point. If two or more points are memorised anywhere on the screen, a midpoint or bisector between the two can be found easily. However, this system still does not overcome the typical problem of profile projectors: indeterminate edges under high magnification.

To determine centre-coordinates and diameter, a minimum of three points must be entered as in *(c)* above. Of course, four points *(d)* will produce a more accurate circle than three. Based on the input given, 2D software calculates the hole centre relative to X–Y origin and its diameter derived from "best-fit" or least-square method. To put it another way, even if the hole is triangular, the diameter calculated by most software will be reported as if it is a perfect circle.

Vision Systems

Unlike profile projectors, vision systems are controlled entirely by computer software such as this one. They feature functions similar to CMMs (encircled in red).

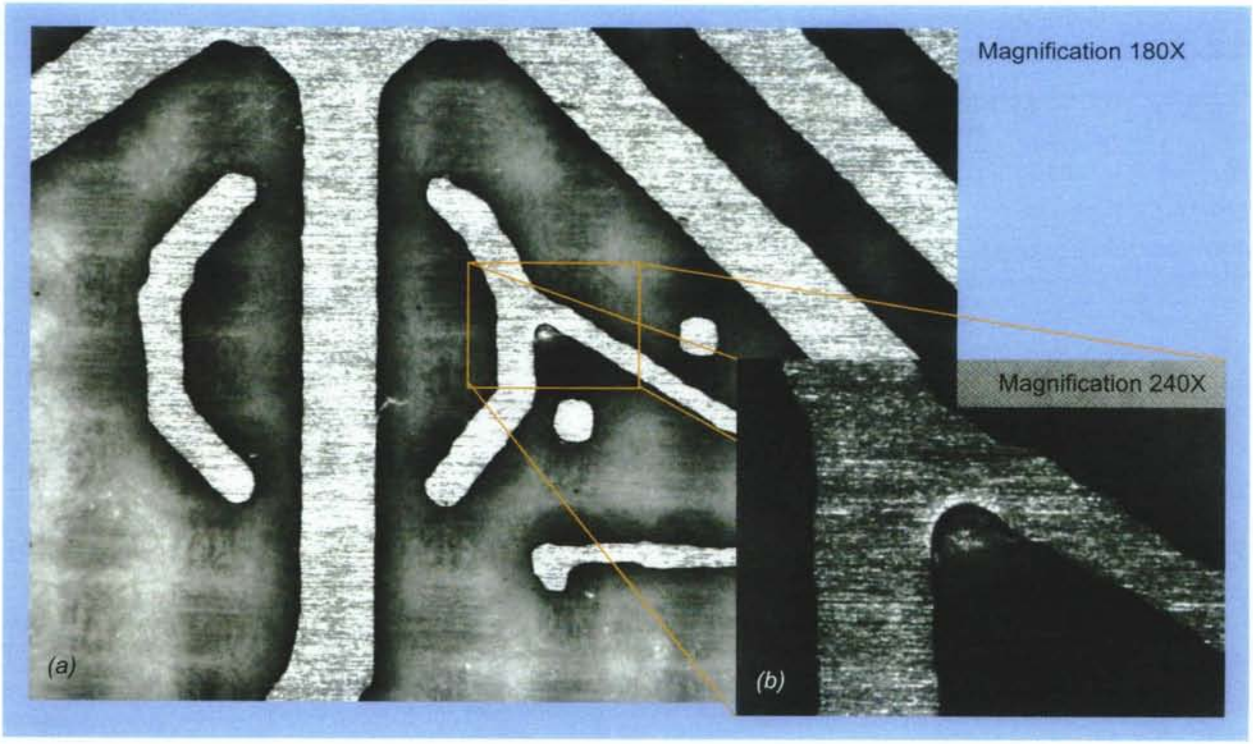
There are a number of advantages in using CCD camera-based technologies. Finding the edge, for example, is a chore for operators of profile projectors as the judgment of operator is required (see page 207), which is eliminated by the use of shape recognition software in vision systems.

Introduced after the invention of the CMM, vision system software *(a)* possesses a set of functions similar to CMMs. Unlike CMMs, vision systems are dependent on lighting conditions. CMMs and vision systems share similar technologies and software, and yet there are several fundamental differences between them: CMMs rely on contact methods while vision systems use non-contact methods.

Contact methods such as touch trigger probes must "touch" and "trigger" as it moves along the work surface, taking about 1 second to register each contact. Although it sounds like a short period of time, a lengthy period may be required when there are more than 300 or more points to register: for example an engine block.

Comparison between two systems	
Profile Projectors	**Vision Systems**
Conceived with the presence of an operator in mind who stands and looks into the screen. Maximum magnification of about 100X.	Invented using pattern recognition technologies, a Vision System can be easily integrated into an automated production line. Much higher lens magnification than the profile projectors. The captured image can be e-mailed with a click of a mouse.

The non-contact system, such as the one shown above, is faster simply because there is no need for a touch trigger. If all features are generally normal to the datum plane, or the surface of the workpiece is 2-dimensional, a non-contact system is superior. The weakness of the non-contact system is in the measurement of Z-axis by the focal plane, as there is a small uncertainty associated with it. For that reason some QC engineers call it the "2½-axis system", instead of 3. However that is now no longer the case, with the advent of the touch trigger probe, the Renishaw TP20, integrated into the vision system. See example *(c)* on the following page.

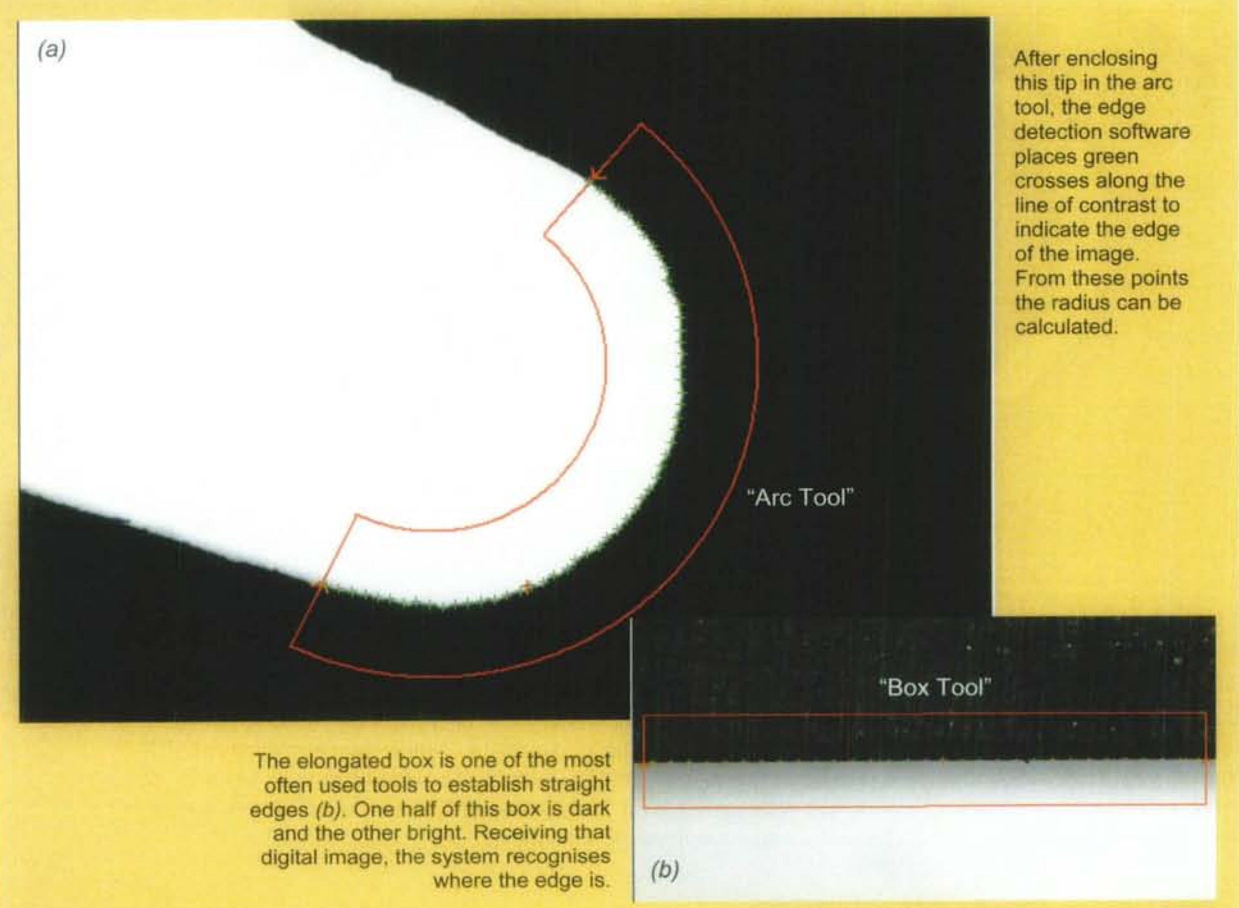


The advent of CCD camera and pattern recognition technologies brought us another powerful tool in the high-resolution inspection arena. This time, the magnification is much greater than anything in the past, barring electron microscopes, with values going up to 960X. Since the image captured is digital, any view on the monitor can be saved and be sent by e-mail. The above images *(a)* and *(b)* were extracted from a zoom lens. Once was known as a "2½-D system", this system now is a more complete 3D measuring system by including a touch probe (see inset).

One of the few weaknesses in the original vision systems was the lack of the measurement in the Z-axis. To attain Z-axis reading accuracy, the focal plane must be very thin. When the CCD camera-based non-contact vision system adapted a touch probe (TP-20) transplanted from the CMM, Z-axis measurements became less ambiguous and more comparable to the regular CMMs. The TP20 touch probe shown at left *(c)* is now integrated in the system and placed next to the lens system. The touch probe measures the three axes XYZ with certainty. For certain features the non-contact method is more advantageous, while for others a contact method may be more desirable. This flexible system offers both.

Comparing CMMs and the vision systems briefly covered this chapter: CMMs are 3D measuring systems, as are vision systems now. Vision systems can magnify the feature under observation, while CMMs cannot. In actual applications, vision systems are preferable for products which are very small and delicate, such as IC-chips, medical and computer devices, pharmaceutical products, etc.

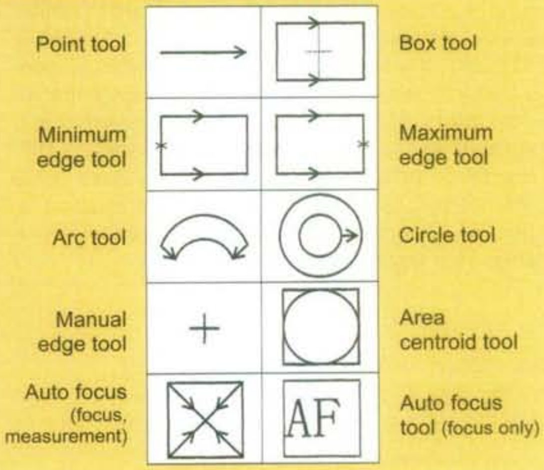
Edge Detection Tools



After enclosing this tip in the arc tool, the edge detection software places green crosses along the line of contrast to indicate the edge of the image. From these points the radius can be calculated.

The elongated box is one of the most often used tools to establish straight edges *(b)*. One half of this box is dark and the other bright. Receiving that digital image, the system recognises where the edge is.

Toolbox to capture the image



Detecting edges is a critical issue for vision systems with high-magnification lenses. Without an edge established, there can be no dimensions to be reported.

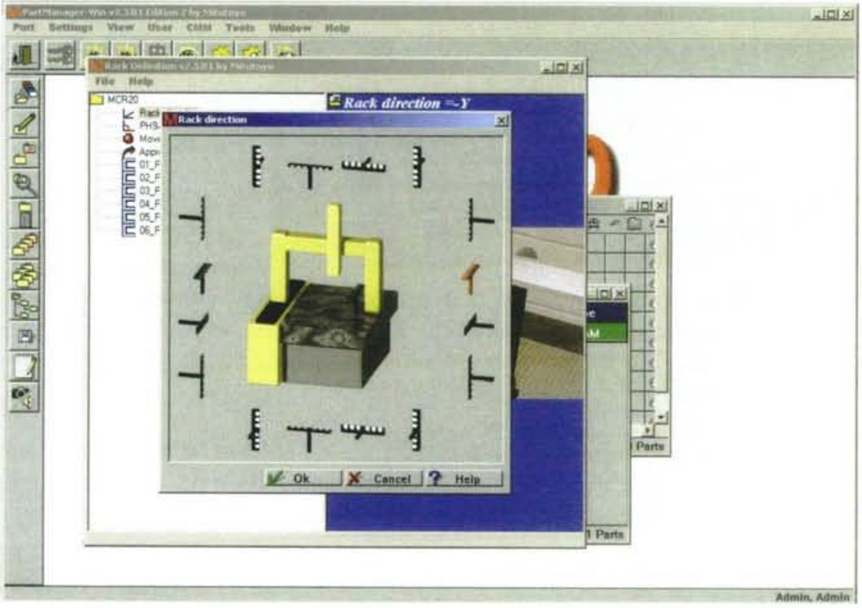
A pattern recognition system can detect a single four-leaf clover in a field of three-leaf clovers, once an appropriate pattern is memorised. Similarly, this application contains a set of tools to aid in establishing all important edges. This method works wherever it detects a contrast in colour in the field of view.

A magnified circle, for instance, can be measured in a variety of ways depending on which characteristic is the subject of interest.

Chapter 14

Coordinate Measuring Machines (CMM)

“A WHOLE NEW TECHNOLOGY”

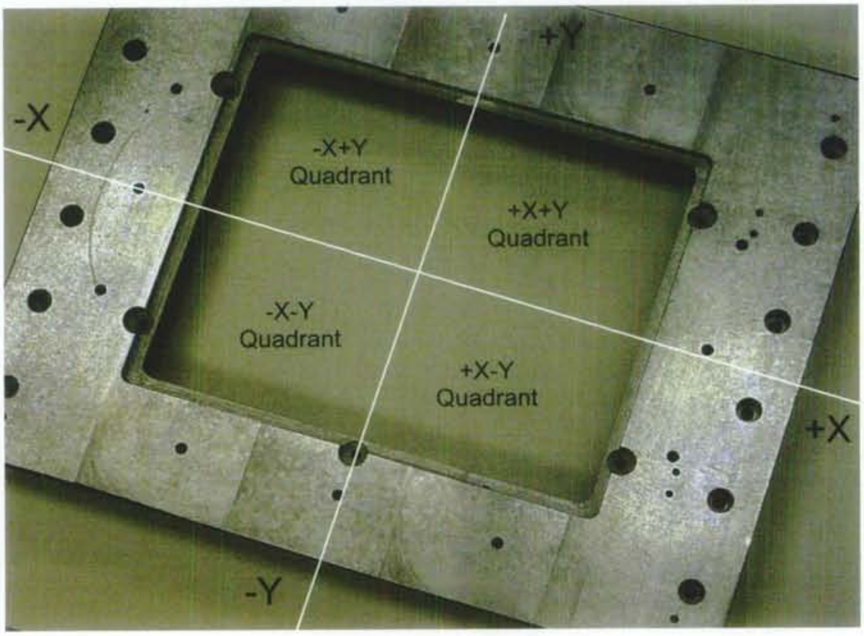


According to eye-witness reports, the first Coordinate Measuring Machine (CMM) was shown at the International Machine Tool show in Paris in 1958. It was displayed by a company called Ferranti, a leading manufacturer of NC machines.

It was clear from the outset that the arrival of a new technology — NC machines — would greatly affect the time required in metal removing. Instead of skilled machinists, the machines would do the job as instructed by a tape; a quantum leap forward in manufacturing technologies. There was one small obstacle to the dramatic speed presented by the new generation of machinery. When the first article came off the NC machine, and it went into QC department for verification, inspectors took a long time to validate it against the prints.

High-speed machines require high-speed measuring methods, with the painfully slow conventional measuring process being the bottleneck. Unless a new method of inspection comparable to the speed of the NC machine could be invented, the future of NC machines looked bleak. The advent of CMM solved this, and brought a terminology called “Cartesian” (X-Y-Z), named after René Descartes (1596-1650) the French philosopher and mathematician. This chapter attempts to briefly describe why CMM is imperative in dimensional inspections.

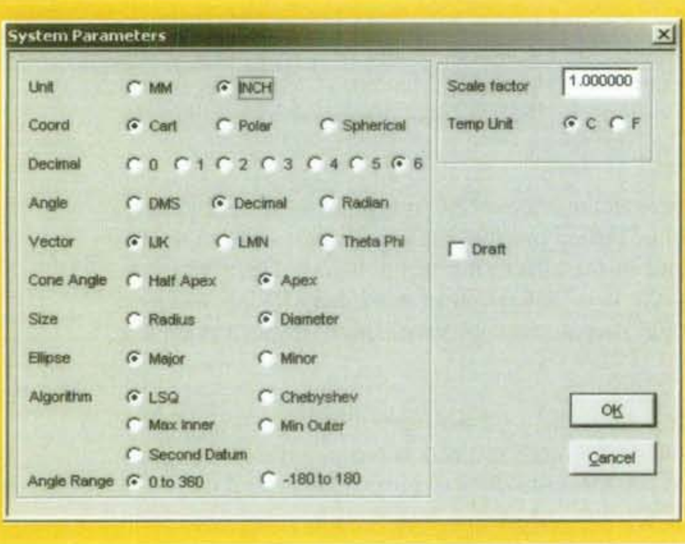
The Cartesian (X-Y) Coordinate System



The "Cartesian" coordinate system, or more commonly called X-Y coordinates, was named after the 17th century philosopher and mathematician René Descartes (1596-1650). His inquiry into the nature and structure of physical universe made him stand out from the rest of his contemporaries, and is known to be one of the most learned men in his time. In 1637, he published '*La Géometrie*' which is a subject of intense study by modern-day QC engineers and operators of coordinate measuring machines even today.

It is the Cartesian coordinate system that is the core of the entire CMM system. The Polar coordinate system, shown on the facing page, is derived from the Cartesian system. The Cartesian coordinate system makes use of 2 axes, called the X and Y axes, which are perpendicular to each other. This divides the possible locations into 4 different quadrants, shown at above left, with the origin (X=0, Y=0) at the centre.

It is clear that René Descartes recognised "Zero". On the other hand, it is unclear if he also recognised negative numbers beyond Zero point. If he didn't, his followers must have completed and perfected the 3D, XYZ coordinate system as we know it today.



Unit ○ MM ● INCH

Coord ● Cart ○ Polar ○ Spherical

Decimal ○ 0 ○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ● 6

Angle ○ DMS ● Decimal ○ Radian

Vector ● IJK ○ LMN ○ Theta Phi

Cone Angle ○ Half Apex ● Apex

Size ○ Radius ● Diameter

Ellipse ● Major ○ Minor

Algorithm ● LSQ ○ Chebyshev ○ Max Inner ○ Min Outer ○ Second Datum

Angle Range ● 0 to 360 ○ -180 to 180

Scale factor 1.000000

Temp Unit ● C ○ F

☐ Draft

CMM software provides a "System Parameters" page, which dictates how the program will behave and output data.

In this page, you can specify whether to use inch or metric, and also what coordinate system to be used. There are three options: Cartesian (X-Y), Polar, or Spherical coordinate systems.

Cartesian is most commonly used system. In fact, the entire CMM hardware is based on it, with other coordinate systems derived from it.

The Polar Coordinate System

A Bolt Circle with 8 holes equidistant from the centre axis (A). Each hole centre is supposed to be 45° apart with the centre axis as Datum A. This can be verified using the Polar Coordinate System.

A similar case to the above, this Bolt Circle has 7 instead of 8 holes.

Here are two picture-perfect examples of Bolt Circle (BC) patterns *(a)* and *(b)* where each hole must be located equidistant from the centre axis. Depending on how this part will be fitted with the mating part, Datum and Datum feature will be indicated by the designer. It may be specified on the internal bore surface (A) or on its axis. Either one may be designated as Datum A. Another circle (B) must be concentric with respect to Datum A, so will be the 8-hole bolt circle and each hole centre located at 45° to each other. "True" Position is likely to be added here.

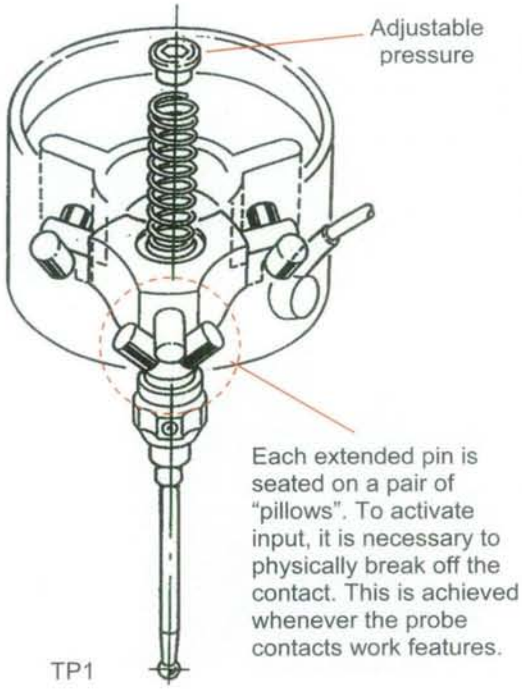
How was this bolt circle measured before the CMM? Inspectors worked with a test indicator, a granite table and a chart of trigonometric functions. What if, the example *(a)* was specified with a position ("true" position) callout of 70 µm (.003 in), how did they do that?

Polar Coordinates are seamlessly converted from the base Cartesian coordinates (facing page). The third coordinate system, Spherical Coordinates, is also derived from Cartesian coordinates. Polar coordinates indicate the target location in terms of R (distance from a fixed point) and θ (theta: angle from origin line).

For the value of θ, some machinists prefer to use "Minus 15 degrees", as opposed to "345 degrees". In this school of thought, the entire circle is divided into two halves: 0 to 180° and 0 to Minus 180°. Most often it is expressed in Degree-Minute-Second; however this DMS can be flipped over to a decimal degree system.

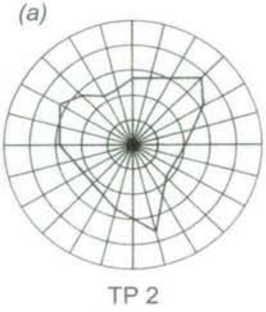
See example *(b)* above. If the threaded hole (C) happens to be Datum A, a thread gauge pin must be inserted. Other methods may be more cumbersome.

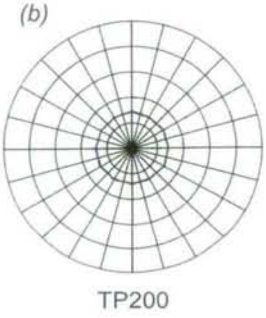
The Touch Trigger Probe



Each extended pin is seated on a pair of "pillows". To activate input, it is necessary to physically break off the contact. This is achieved whenever the probe contacts work features.

Both of Renishaw's TP1 and TP2 display a triangular lobe condition due to its three-legged trigger mechanism as illustrated above. Depending on which direction the TP1 and TP2 move, the trigger point varies as shown in chart *(a)* here.





The latest series of Renishaw's probe, the TP200, no longer displays variations in trigger point regardless of the direction approached. As a result, overall accuracy of CMMs improved dramatically.

Without the invention of the touch trigger probe by Renishaw during the 1970s, the most significant and promising measuring system of all, the CMM, could not have seen the wide acceptance it deserved; without the touch trigger probe, the advancement in the total CMM system would have been next to impossible. As its name implies, the probe touches the workpiece, freezes the XYZ display and reports the coordinates relative to various Datum.

The very first touch probe by Renishaw aptly named TP1 (illustrated at left), was introduced many years after the introduction of CMM. It was invented by David McMurtry of the then Rolls-Royce PLC. He wanted to solve the problem of measuring pipes for the Olympus engines on the supersonic Concorde aircraft: when bent pipes are presented, it is not the diameter of pipe that matters but rather the vector or radius created by the pipe that connect one element of the jet engine to another. His invention, the TP1, improved the repeatability and accuracy of the CMM many fold by virtue of triggering at the point contacted. Although it resembled a relay with only "On" or "Off" states, this was nothing short of a breakthrough. The hard probes that existed earlier disappeared instantly after this invention.

After countless innovations and improvements, the historic TP1 evolved into the TP2 which has been a best seller for many years. Since it was evolved from the original design, the TP2 also displayed characteristic tendency of a "three-lobe condition" as illustrated in Chart *(a)* at left. The TP1 featured three-legged prongs and a pair of "pillows" for each prong, and thus possessed a tendency of creating triangular lobe conditions. Trigger input would vary depending on from which direction the probe came in contact with the work surface. At times, the so called "pre-travel" varied as much as 10 μm (.0004 in). The arrival of the TP200 based on piezo sensors removed that problem.

Furthermore, because the probe is dependent on contacting internal surfaces, namely the three prongs in contact with three pairs of pillows, reliability and probe life can be a factor in some heavy applications. To this end, special materials and lubricants have been developed to extend the probes' working life; however, this design can be only expected to function reliably within a framework of metal fatigue and wear. Some present day applications are require over a million triggers a year, and with more automated CMMs in use, the touch trigger probe must work harder than ever.

The Analogue Probe

Some call this type of probe an "analogue" type probe. Unlike more familiar touch-trigger probe, which touches and detaches from the work surface, this probe stays in contact with the surface throughout its operation and "creeps along" on its own.

While the probe is in motion and in contact, data will be transmitted to the computer. Depending upon the data density required and geometry of specimen, the probe can take in data every 2.5 µm (.0001 in). Without this probe technology, analysing curved surfaces may be difficult. Contour tracing instrument with tracing arm will also provide a similar result, but requires a specialised instrument unlike the general purpose CMM

One way to measure curvature is to use a CMM with an analogue probe which stays in contact and generates data as it "creeps" along the workpiece. The operator's choice in this case is to use the smallest contact point available to avoid potential cosine error. One such example *(a)* is shown on the left. Resolution in this case is in microns (µm) but can be smaller.

There is another method to detect contours, called "Contracer", short for "contour tracer". This method employs a tracing arm that magnifies the traced contour, much like the probe that detects surface roughness. The magnification in the contracer is limited to 200X for contour tracing. By contrast, surface roughness probes magnify 10,000X or more. Contour tracing instruments with a low magnification of 200X can be used to detect features much more dense and complicated than the above method, because it magnifies.

Although the analogue probe shown above *(a)* cannot magnify the contours, but it still is able to generate the coordinates. For this particular workpiece a general purpose machine like the CMM with an analogue probe may be the answer.

The Renishaw TP20 Probe

Probe module

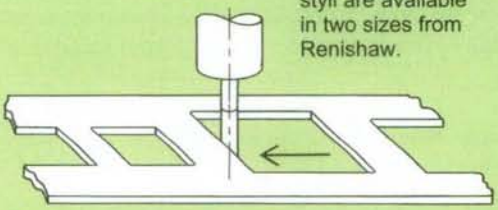
Standard force module

Cylindrical ruby stylus for sheet metals with punched or chemical-etched slots

Kinematic coupling between the probe body and module affords limited (probe module only) crash protection in the X-Y planes.

The new TP20 was designed to replace the earlier model, TP2, which is still the most widely used touch trigger probe in the market. According to Renishaw, one of the significant changes brought by this new probe is its ability to change stylus configurations manually or automatically without re-qualification. In theory, it is no longer needed to touch the master sphere again after the probe module has been replaced. A selection of additional modules for various purposes is also available.

The touch probe trigger mechanism plays a critical role in the accuracy of CMM. What it must do is to repeat and repeat well, and trigger the inputs regardless of which direction the probe approaches the workpiece. The TP20 and TP200 are the latest probes and are significantly improved over the earlier TP1 and 2. The TP20 allows the probe to break off in the unlikely event of a crash. However, the Triangular "three-lobe condition" still exists in TP20, but it is almost unnoticeable under TP200.

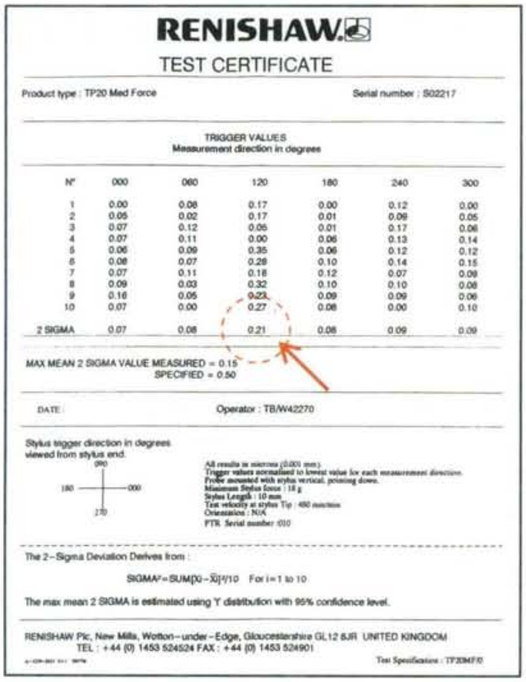


Cylindrical ruby styli are available in two sizes from Renishaw.

The edges of the punched sheet metals are difficult to measure with a standard ruby ball. The thinner the sheet metal, the harder it becomes to contact. It will be much easier if the stylus is made of a cylindrical ruby as shown above.

With this interchangeable cylindrical ruby stylus, the sheet metal job will be much easier. Simply move the probe in X-Y plane. If workpieces are placed flat, Z-axis may be locked for greater throughput.

(a)



RENISHAW

TEST CERTIFICATE

Product type : TP20 Med Force

Serial number : 502217

TRIGGER VALUES
Measurement direction in degrees

N°	000	060	120	180	240	300
1	0.00	0.08	0.17	0.00	0.12	0.00
2	0.05	0.02	0.17	0.01	0.09	0.05
3	0.07	0.12	0.05	0.01	0.17	0.06
4	0.07	0.11	0.00	0.06	0.13	0.14
5	0.06	0.09	0.35	0.06	0.12	0.12
6	0.08	0.07	0.28	0.10	0.14	0.15
7	0.07	0.11	0.18	0.12	0.07	0.09
8	0.09	0.03	0.32	0.10	0.10	0.08
9	0.16	0.05	0.23	0.09	0.09	0.06
10	0.07	0.00	0.27	0.08	0.00	0.10
2 SIGMA	0.07	0.08	0.21	0.08	0.09	0.09

MAX MEAN 2 SIGMA VALUE MEASURED = 0.15
SPECIFIED = 0.50

DATE :

Operator : TB/W42270

Stylus trigger direction in degrees
viewed from stylus end.

All results in microns (0.001 mm).
Trigger values normalised to lowest value for each measurement direction.
Probe mounted with stylus vertical, pointing down.
Maximum Stylus force : 18 g
Stylus Length : 10 mm
Test velocity at stylus Tip : 480 mm/min
Orientation : N/A
PTR Serial number 010

The 2–Sigma Deviation Derives from :

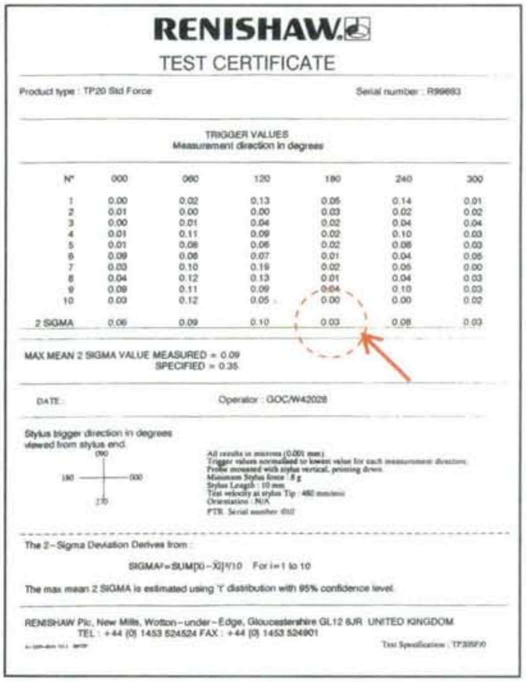
SIGMA²=SUM[Xi–X̄]²/10 For i=1 to 10

The max mean 2 SIGMA is estimated using 't' distribution with 95% confidence level.

RENISHAW Plc, New Mills, Wotton–under–Edge, Gloucestershire GL12 8JR UNITED KINGDOM
TEL : +44 (0) 1453 524524 FAX : +44 (0) 1453 524901

Test Specification : TP20MF0

(b)



RENISHAW

TEST CERTIFICATE

Product type : TP20 Std Force

Serial number : R99693

TRIGGER VALUES
Measurement direction in degrees

N°	000	060	120	180	240	300
1	0.00	0.02	0.13	0.05	0.14	0.01
2	0.01	0.00	0.00	0.03	0.02	0.02
3	0.00	0.01	0.04	0.02	0.04	0.04
4	0.01	0.11	0.09	0.02	0.10	0.03
5	0.01	0.08	0.06	0.02	0.08	0.00
6	0.09	0.08	0.07	0.01	0.04	0.05
7	0.03	0.10	0.19	0.02	0.05	0.00
8	0.04	0.12	0.13	0.01	0.04	0.03
9	0.09	0.11	0.09	0.04	0.10	0.03
10	0.03	0.12	0.05	0.00	0.00	0.02
2 SIGMA	0.06	0.09	0.10	0.03	0.08	0.03

MAX MEAN 2 SIGMA VALUE MEASURED = 0.09
SPECIFIED = 0.35

DATE :

Operator : GOC/W42028

Stylus trigger direction in degrees
viewed from stylus end.

All results in microns (0.001 mm).
Trigger values normalised to lowest value for each measurement direction.
Probe mounted with stylus vertical, pointing down.
Maximum Stylus force : 8 g
Stylus Length : 10 mm
Test velocity at stylus Tip : 480 mm/min
Orientation : N/A
PTR Serial number 010

The 2–Sigma Deviation Derives from :

SIGMA²=SUM[Xi–X̄]²/10 For i=1 to 10

The max mean 2 SIGMA is estimated using 'T' distribution with 95% confidence level.

RENISHAW Plc, New Mills, Wotton–under–Edge, Gloucestershire GL12 8JR UNITED KINGDOM
TEL : +44 (0) 1453 524524 FAX : +44 (0) 1453 524901

Test Specification : TP20SF0

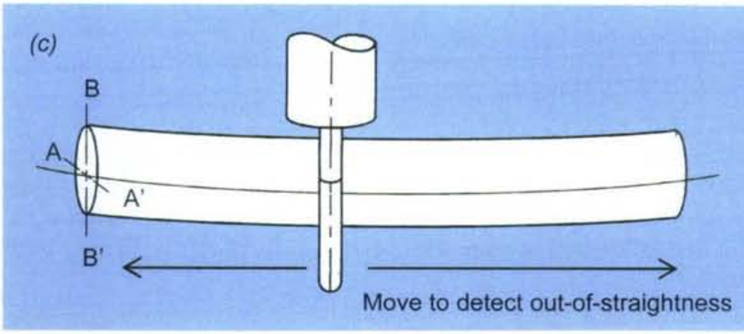
The TP20 is supplied in a prearranged pair of medium and standard force probe modules. Contact pressure is the dividing factor between the two; it can be measured by a gram gauge, but data is also available from Renishaw. Contact pressure is the hardest extended force module used to attach heavy extensions.

TP20's range of Probe Modules

Low force Module	Standard force Module	Medium force Module	Extended force Module

The TP20 was developed to replace existing TP2: the method of replacement is a snap, literally. Simply snap the TP2 off and replace it with a TP20.

Renishaw's repeatability certificate supplied with TP20 is very complete. In the 2 randomly selected certificates above *(a)* and *(b)*, as many as 60 test data is recorded. This is the repeatability test where TP20 probe approaches the target from six different directions 60° apart, repeated ten times into a given direction. Observe the worst data at 120°: 0.21 means 0.21 μm, indicated by the arrow in *(a)*, is expressed in 2 sigma level, a common practice in stating repeatability. 0.21 μm is nearly 8 micro-inches (.000008 in) which is the worst case in the above certificates. Comparing two certificates side by side, it is clear that the standard force probe *(b)* displays a better repeatability (see arrows). 0.10 μm encircled above is 4 μin (.000004 in).



The cylindrical ruby point on the opposing can check diameter of a rod such as this example *(c)*. It will also help detect the out-of-straightness condition as the probe is moved from left to right. Upon finishing A-A' direction, turn the bar 90° for B-B' direction.

Calibration of CMM

Renishaw's He-Ne laser calibration equipment being used to calibrate a CMM.

Courtesy: Renishaw Inc.

The key to this method is to have a set of accurate mirrors and reflectors shown at right *(b)*, mounted on the Z axis. The mirror bounces back the coherent red light generated by the laser interferometer.

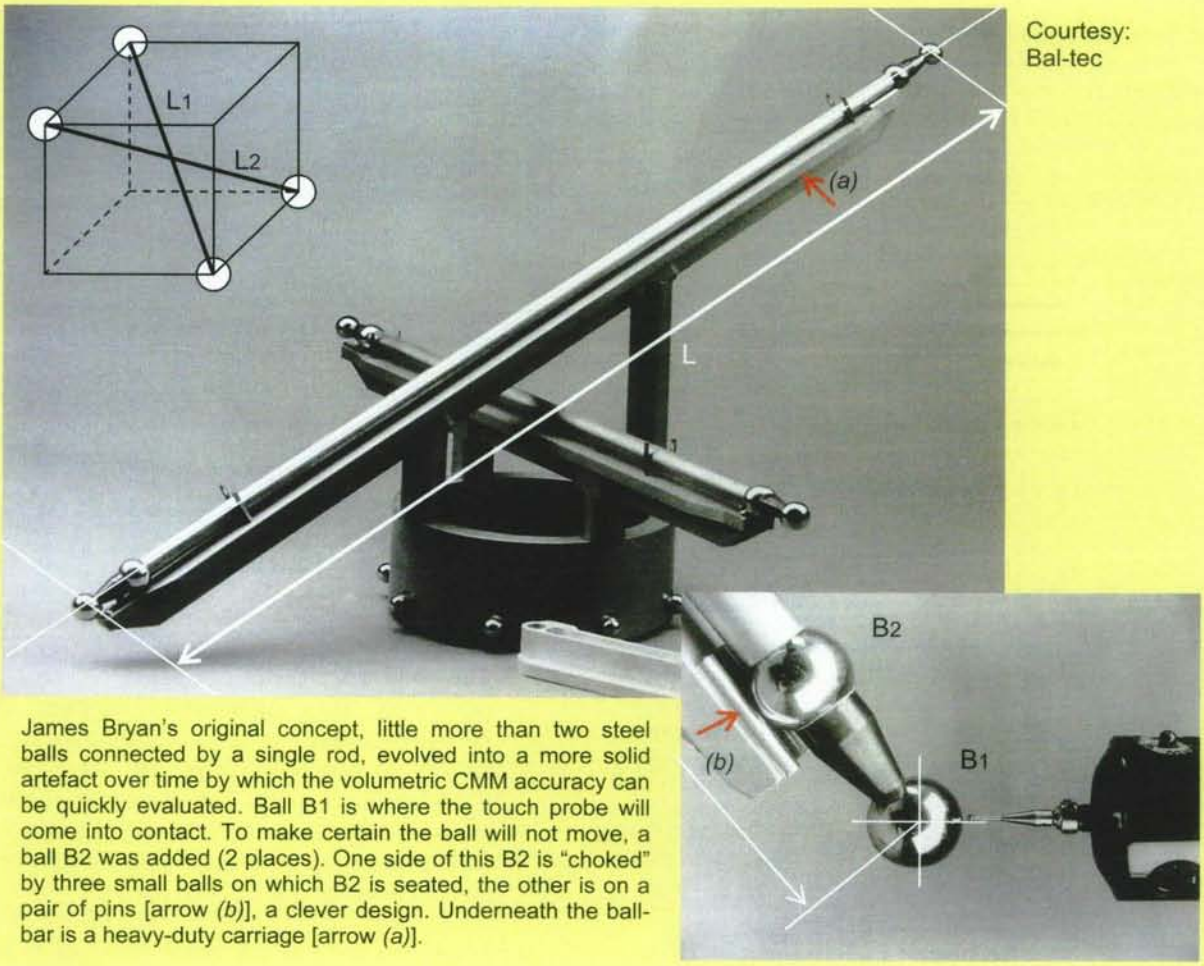
It started with the Hewlett-Packard in the 1960s, and machine tool builders were quick to use this method in aligning large machines. CMM is a measuring machine and some are so large that laser interferometer is the only way to calibrate distances. Example *(a)* is a more recent Renishaw system for this application.

HP5518A Model and targets

Regular-size CMMs up to 2 m (80 in) in measuring length can be calibrated by hard gauges such as gauge blocks and step gauges. When the CMM range exceeds 2 meters, then laser may be a better way; hard gauges that are 2 meters long and beyond are considered heavy equipment, while laser interferometers are more compact and can calibrate longer lengths. As a rule of thumb, the linear accuracy of a laser may be understood as about 5 µm for every 1 meter under normal conditions; when environmental conditions improve, as does the accuracy of the laser.

The wavelength of lasers tend to increase very slightly over time, the amount of change is in a few femtometres (millionths of a nanometre) and it will not get shorter. It is safe and even correct to say that the wavelength remains constant. In actual practice, a disturbance of air in the room affects the accuracy. This laser equipment can be recalibrated at a branch of NIST in Boulder, CO. Turnaround time for this calibration is about a week.

Determining CMM Volumetric Accuracy



Courtesy:
Bal-tec

James Bryan's original concept, little more than two steel balls connected by a single rod, evolved into a more solid artefact over time by which the volumetric CMM accuracy can be quickly evaluated. Ball B1 is where the touch probe will come into contact. To make certain the ball will not move, a ball B2 was added (2 places). One side of this B2 is "choked" by three small balls on which B2 is seated, the other is on a pair of pins [arrow *(b)*], a clever design. Underneath the ball-bar is a heavy-duty carriage [arrow *(a)*].

During the 1960s and even in the earlier part of the 1970s, each CMM manufacturer stated their accuracy differently. The absence of uniform CMM accuracy troubled James Bryan, then from the Lawrence Rivermore National Laboratory. He could not tell if brand A was more accurate than B, unless a device (standard of length) existed to measure CMM accuracy.

He invented such a standard, and it had the added advantage that it could be carried in anyone's briefcase. The length of a Ball Bar can be any length; what matters is the length between the two hardened spheres L remains constant as the Ball Bar is measured in various positions by the CMM, for example, diagonally as illustrated (L_1 and L_2).

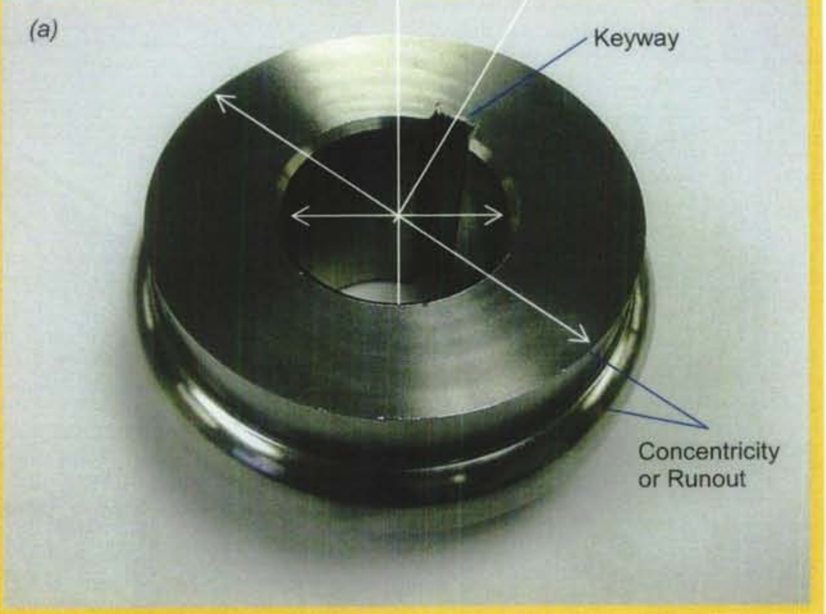
Armed with this ingenious yet innocent-looking bar, James Bryan could visit CMM manufactures and assess the volumetric accuracy of their CMM machines, which is a compounded accuracy of all XYZ axes. This way, not only the squareness of three axes but also touch probe's accuracy was taken into the consideration. The ASME B89.4.1 standard which stipulates how to check CMM accuracy fully supports this method, while ISO counterpart appears to be indifferent.

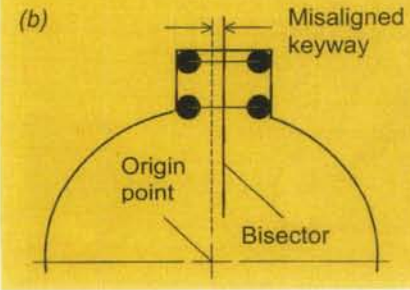
Measuring Keyway/Keyseat

From the presence of a keyway, it is obvious that this workpiece is designed to rotate. Depending upon how it is specified; Concentricity, Circular or Total Runout, and other issues may be associated with this doughnut-shaped workpiece.

Symmetry

The GD&T symbol for Symmetry (three horizontal lines) is the last of the 14 symbols in ASME Y14.5M-1994. Symmetry was not included in the earlier 1982 Y14.5 but added in 1994.

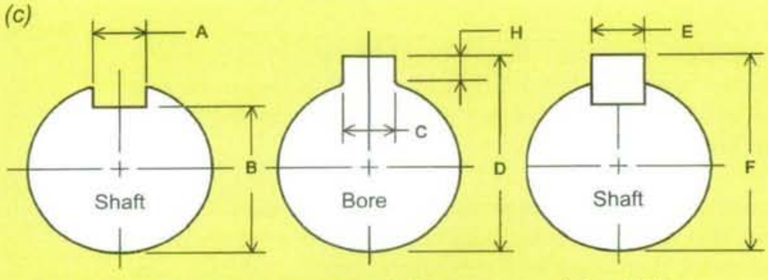




The square key to be inserted is slightly tapered to make assembly easier. The degree of taper is predetermined in reference books such as "Machinery Handbook" 28th Edition.

The only measuring equipment capable of measuring the relationship between the bore/shaft centres to keyways/keyseats is the CMM. As illustrated here *(a)*, there are a number of dimensions that should be checked and validated, not to mention the Runout aspect that may come into play if the workpiece rotates in high speed in real life.

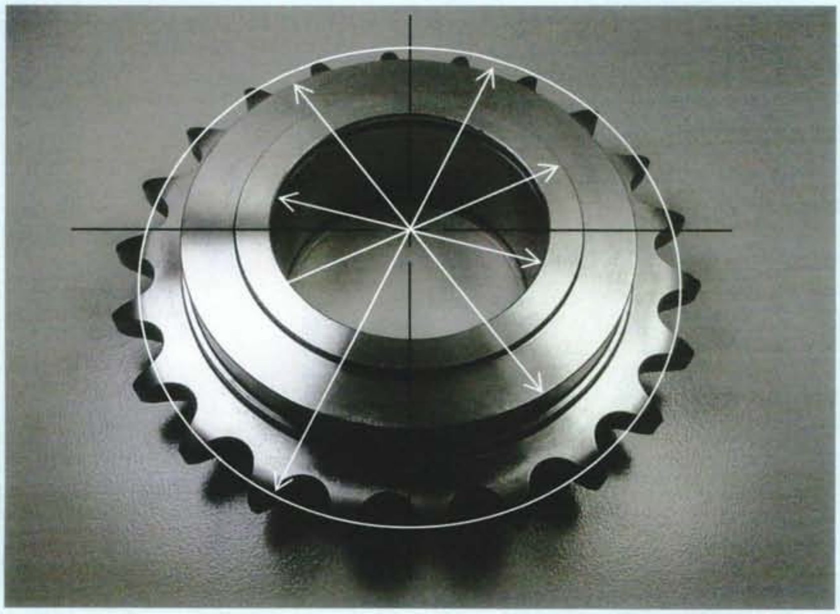
This frequently produced part is much simpler from the viewpoint of geometry. Whether or not symmetry is specified is unknown. Nevertheless the keyway must be cut along the bore's centre line and symmetry is implied, if not specified. For many years, to check the size and see if the key was in line with the axis a Go/No-Go key-slot gauge was used; the advent of CMM made it completely unnecessary.



Arbor & Keyseat   Cutter Bore & Keyway   Arbor & Key

The product designers may pick a known set of numbers for the dimensions A though F. A series of trial and error tests to determine the exact dimensions of this feature may be required: tolerances for the width of keyway C and key E may be tight and they may take "interference fit" if it is to stay there permanently.

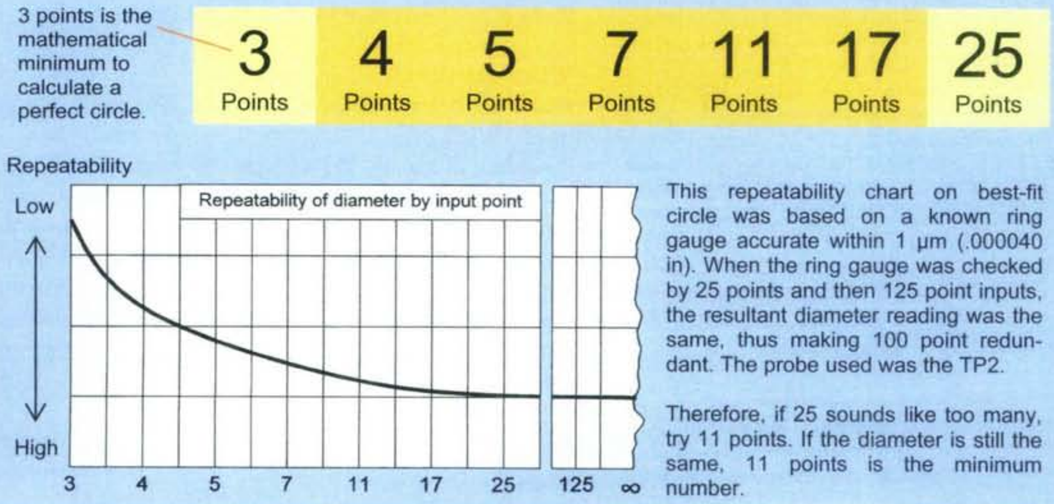
How Many Points?



How many points are required to measure the diameter of a workpiece such as this?

The question: "How many points do I need to measure?" is one of the most often asked questions by CMM operators. The answer should be: any number larger than 3. However, 3 points is never enough to check diameters. In addition, Circularity and Concentricity require more input points.

A 3-point measurement is purely theoretical. Small variations in diameter will be produced if only 3 points are used. Using 4 points – a crucial additional point – provides improved repeatability. If 4 is better than 3, then what's the ultimate number? What if operator A checked a circle with 25 points, while operator B did it using only 7 points and the diameter measured was the same?



3 points is the mathematical minimum to calculate a perfect circle.

This repeatability chart on best-fit circle was based on a known ring gauge accurate within 1 µm (.000040 in). When the ring gauge was checked by 25 points and then 125 point inputs, the resultant diameter reading was the same, thus making 100 point redundant. The probe used was the TP2.

Therefore, if 25 sounds like too many, try 11 points. If the diameter is still the same, 11 points is the minimum number.

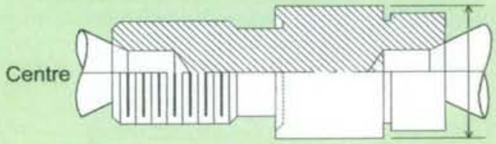
Measuring Threaded Holes

Produced by turning from a solid stock, this position locator will become coaxial to the thread holes when inserted. The touch probe will simply contact the exposed cylinder, whose centre remains coaxial to the threaded holes. When they are specified with "true" position (now called position), the centre coordinates of threaded holes become critical.

Courtesy: Lavezzi Precision

The supplier of this handy accessory calls them "Tru-Pos." Obviously thread size, inch or metric, must be specified. For that reason, it may be wise to order only the size needed and buy one piece at a time.

Coaxiality between the threads and cylinder = 5 µm (.0002 in)



If this threaded plug is produced by the method implied above — held by the centres and turned — the coaxiality or concentricity between the two, threads and cylinder, should be automatic. Note the knurled grip atop the cylinder. It is made smaller than the diameter of the cylinder to stay away from the probe's path. The knurled grip allows easy entry and removal. This cylinder should be twisted "finger-tight".

Perpendicularity (Squareness) of the bottom lip of the cylinder, or seating face, with respect to the threads is 5 µm (.0002 in). Finely ground threads are sized to 2.5 µm (.0001 in) under a Class 2B "go" thread gauge with a -7.5 µm (-.0003 in) tolerance.

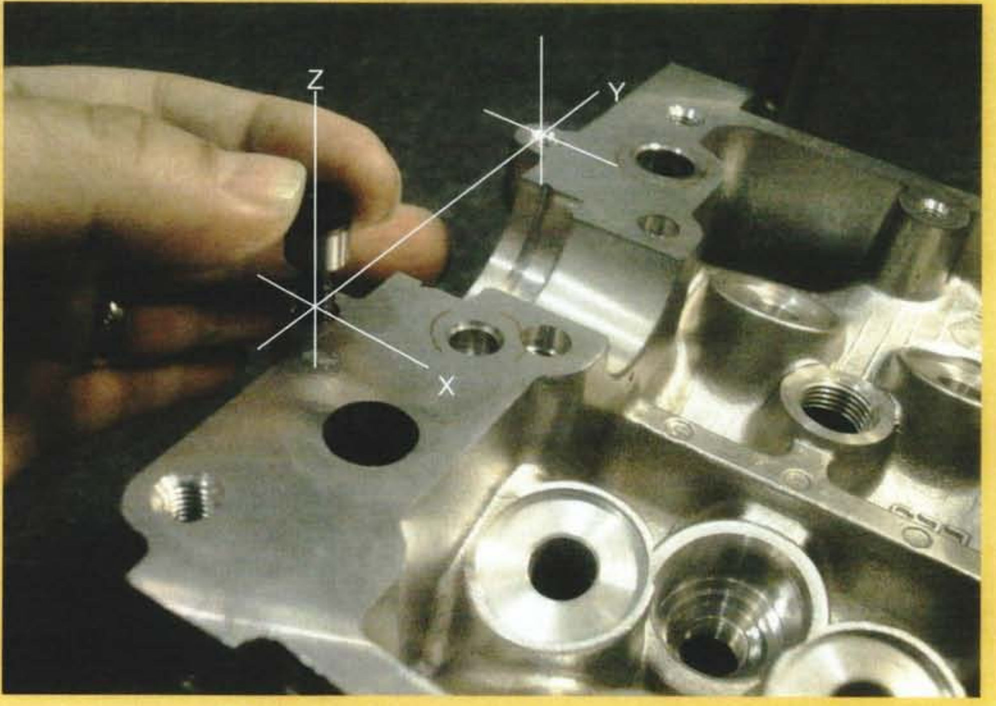
Centre coordinates of larger threaded holes are easy to check even with a standard probe. It is the smaller threaded holes that pose a problem. How to measure them is not described in the CMM manual.

When the threaded holes become very small, the probe diameter must be equally small to enter into the hole. With this arrangement — a small ball in threaded holes — the chance of missing the mark may become a concern. This particular set of accessories attempts to solve this problem. As shown on the facing page, the small cylinders are compared with a paper clip to give a sense of their size. By inserting one such accessory into a small threaded hole, it makes measuring using the CMM much easier and more accurate.

Pick a threaded hole to experiment with and measure its X-Y coordinates with and without this accessory, then check the data generated by two methods.

Small threaded holes pose unproportionally greater problems. To have a probe to go into the bore, the ball must be extremely small to begin with (e.g. a pierced SØ 0.5 mm ruby ball). At this level, one needs good eyesight to check even straight bores. Imagine they are threaded; making determining centre coordinates even more difficult.

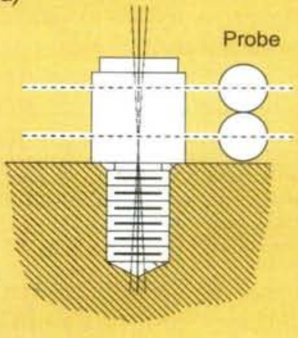
These tiny cylinders may provide much needed assurance as to where the X-Y centre coordinates are. All this takes time, but what else is there to give more confidence than this somewhat time-consuming method? If internal threads are cut, a mating part will be inserted at assembly. Why not test the threaded holes in the first place?



Courtesy: Lavessi Precision

For Manual or CNC models, lock the Z-axis first and probe the tiny cylinders inserted in the threaded bores. The top and bottom two-plane method shown at right *(a)* may work well if the ball size is small enough to do the job. The cylinder surface may be too short to accommodate the two-layer method for a standard probe. If a centre coordinate of threaded hole is shown on a projected plane, simply measure the cylinder with more than 4 points (7 or 11, for instance).

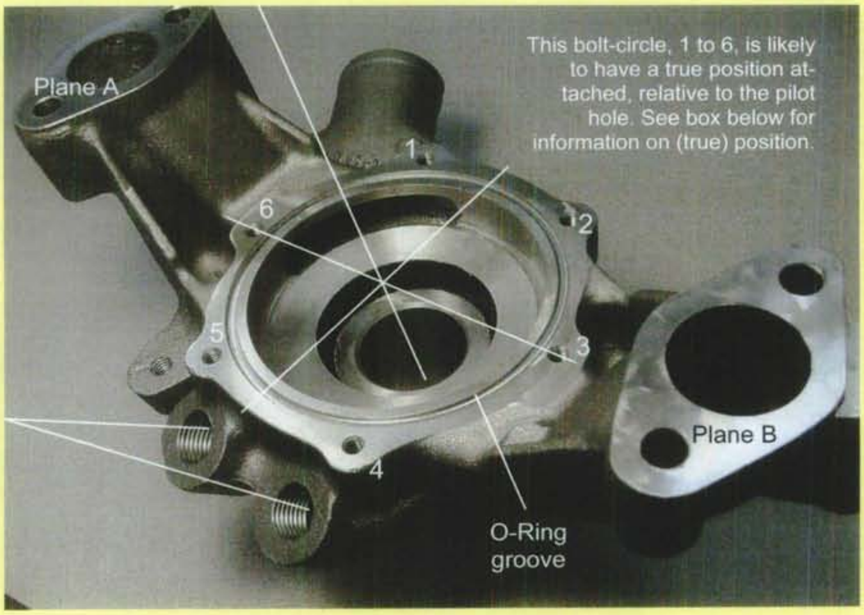
(a)



Because the probe will come into contact above the surface, the plane checked by the touch probe will be projected. The threaded hole axis is generally assumed to be normal to the top surface, and can be validated.

By probing in two layers as shown here, *(a)* at left, the vector of the hole may be found, although it is limited by the short cylinder length. Ball size must be small enough and more than 4 points each should be entered.

Approaches to Measuring



A challenging workpiece for the CMM to measure

The centre of these threaded bores can be checked by a large ball touching minor diameters. For a more accurate assessment see page 226.

(True) Position

(True) Position is one of the most often specified tolerances in the 14 GD&T symbols. Originally known as "True Position" it is now simply called "Position".

It is a concept based on a round patch within which the axis must lie. In the above example, the holes 1-6 must be 60° apart while keeping the same distance from the centre.

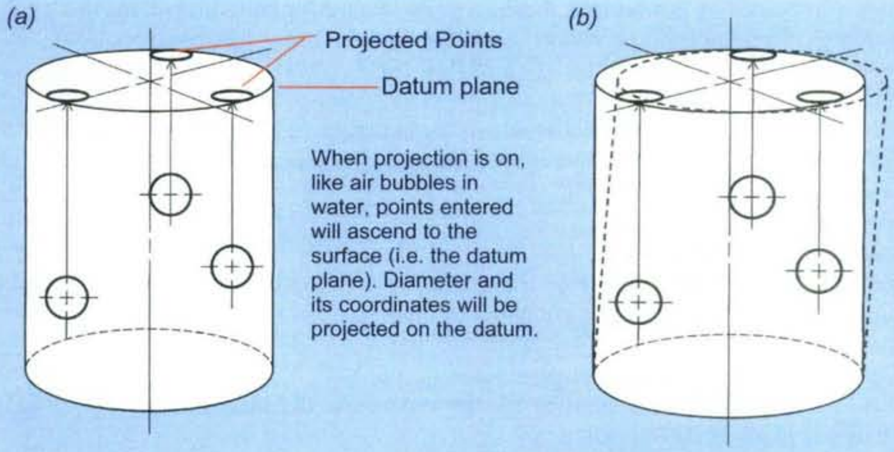
When it is difficult to measure on a surface plate using conventional gauges such as a height gauge, challenging workpieces are often forwarded to the CMM to be measured. While the CMM is most capable of all gauges, particularly for this type of complex cast-iron workpiece (shown above), locating internal threads is one of the CMM's few weaknesses. Bring in the gauge pins, insert them and measure the pins (see page 226 for more). They double as a thread gauge, in addition to correctly locating the centre coordinates. Threaded holes must be checked with a thread gauge to check pitch diameter (a reversible Go/No-Go Gauge will be the best choice).

This bolt circle, 1 through 6, shown above, is likely to be specified with a "Position" tolerance which determines the axis of 6 holes 60° apart placed equidistant from the centre. Positional tolerance does not involve diameter. Diameter is related to size, and for that the limits of size (upper and lower size limits) must be met.

The least problem of all features on the above workpiece appears to be the O-ring groove placed inside the bolt-circle. Groove diameter, width and depth may be the issue here, as well as concentricity. A very small ruby probe (e.g. SØ 1 or 0.5 mm) may be needed to go into the groove and touch both walls.

As for the planes A and B, they are not coplanar and their respective vectors must be determined by probing the surface. Each plane, A or B, has a pair of straight bores flanking the large centre hole which is left untouched by machine. The pair of straight bores can be easily checked by CMM. The points touched by the probe are known sometimes as "local size". For this reason, placing a pin gauge into it is highly recommended.

Projections and Projected Planes



When projection is on, like air bubbles in water, points entered will ascend to the surface (i.e. the datum plane). Diameter and its coordinates will be projected on the datum.

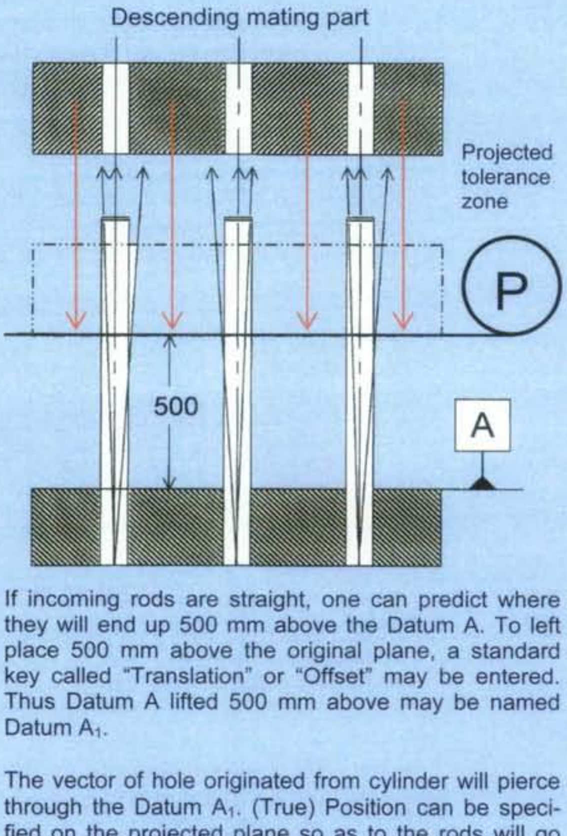
Even if a hole was not drilled normal (90°) to the surface, points entered will go straight to the datum plane whenever Projection key is "ON"

The point where cylinder and plane intersect may be a better way to study geometry.

Hole diameter and its centre coordinates can be measured with a minimum of three points. Many CMM operators recognise the minimum number is correct in a mathematical domain but incorrect in the real world, and intuitively pick four or five points whenever they have to measure a bore. If the minimum point is 3, add one more point and make it 4 to measure the circle; 5 is better but 7 is much better. Using a greater number of input values is known as "Extended Accuracy" in some CMM software. Regardless of the input number, it will be projected to a datum, and the diameter thus calculated is two dimensional in nature.

When the holes get deeper, rods will need to be inserted as in this example at right, the vector of holes becomes critical, especially when the mating plane is away from Datum A. The mating will stop at 500 mm above as illustrated. If the rod exceeds the 10 to 1 ratio (e.g. 100 mm in length to 10 mm in diameter) the straightness of the rod must be considered. There should be a pilot hole to guide the assembly. There is a good reason not to measure holes simply as a circle with a 3 point minimum, but to measure them as a cylinder using 6 or more points.

If two geometric elements exist: one a cylinder and the other a plane, cylinder will intersect the plane at one point, unless otherwise they are parallel to each other. Such a piercing point should be used as the centre coordinate.



If incoming rods are straight, one can predict where they will end up 500 mm above the Datum A. To left place 500 mm above the original plane, a standard key called "Translation" or "Offset" may be entered. Thus Datum A lifted 500 mm above may be named Datum A_1.

The vector of hole originated from cylinder will pierce through the Datum A_1. (True) Position can be specified on the projected plane so as to the rods will go through the hole in assembly if this is a clearance fit. As indicated in the drawing *(a)* and *(b)*, projection is either "On" or "Off" during the measurement.

Summary

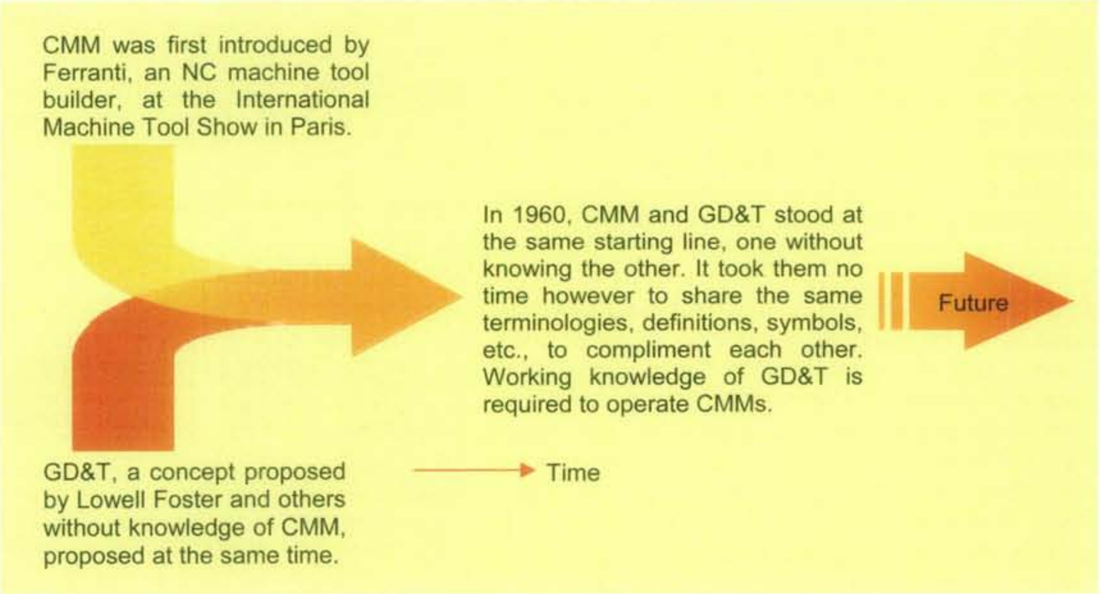
In the short history of precision measurement, there are only two outstanding inventions that changed the course of metrology profoundly: (a) creation of steel gauge blocks by Johansson in 1900, and (b) introduction of coordinate measuring machines (CMMs) in 1960.

Johansson started to work on what he originally called "combination" gauge blocks earlier than 1900, but it is the symbolic year assigned to his invention during which he reached the smallest dimension then known: one micrometre (1 μm or .000040 in).

Some 60 years later came another breakthrough. Developed by an NC machine tool builder, this new invention was called CMM. It was rushed into the market to cope with the new bread of machines called NC machines. From the outset, high throughput of measurement was the reason for CMMs.

The advent of CMMs introduced a three-dimensional concept; X-Y, Y-Z, and Z-X planes. With the CMM, for the first time, anyone could measure the dimensions in the method it should have been done — from the datum plane or datum axis.

This brings us to yet another significant development took place concurrently buy independently: Geometric Dimensioning & Tolerancing (GD&T). Spearheaded by Lowell Foster of Minneapolis, this concept gave rise to the current standard ANSI Y14.5M-1994 (ISO 1101).



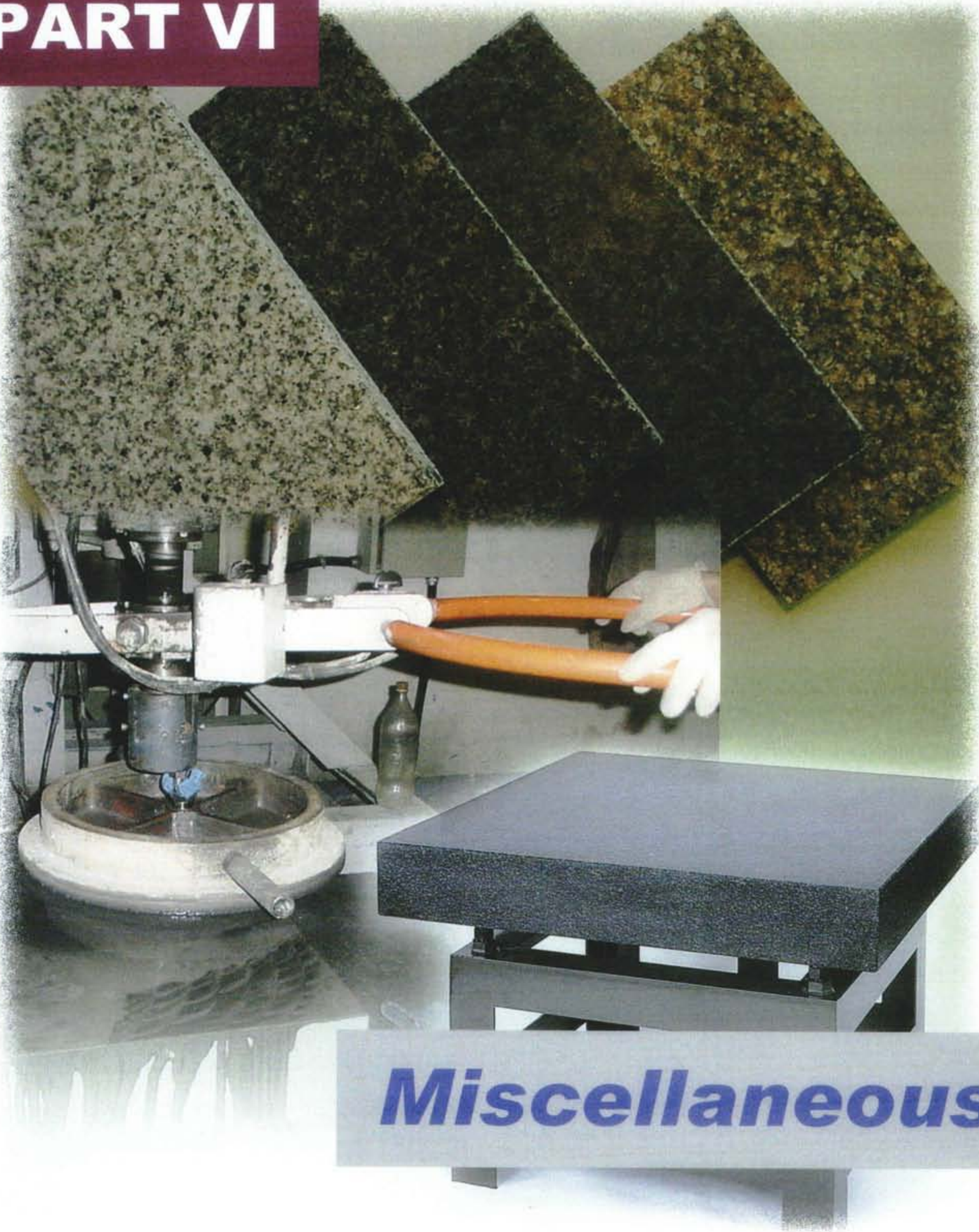
CMM was first introduced by Ferranti, an NC machine tool builder, at the International Machine Tool Show in Paris.

In 1960, CMM and GD&T stood at the same starting line, one without knowing the other. It took them no time however to share the same terminologies, definitions, symbols, etc., to compliment each other. Working knowledge of GD&T is required to operate CMMs.

GD&T, a concept proposed by Lowell Foster and others without knowledge of CMM, proposed at the same time.

The first CMM, when it was introduced in the market, featured no LED, no LCD, no touch probe, no computer, and limited Z-axis movement. The adding machine was there but the word "software" was not invented yet. David McMurtry's ingenious three-pronged device (Page 218) paid off handsomely not only for his company, but also for the users of CMM. With it, a CNC driven CMM became possible. Limited in the touch-trigger method originally, it can now stay in constant contact with the work surface to correct more data points (Page 219). A probe with a non-contact CCD camera is now common place these days.

PART VI



Miscellaneous

PART VI
MISCELLANEOUS

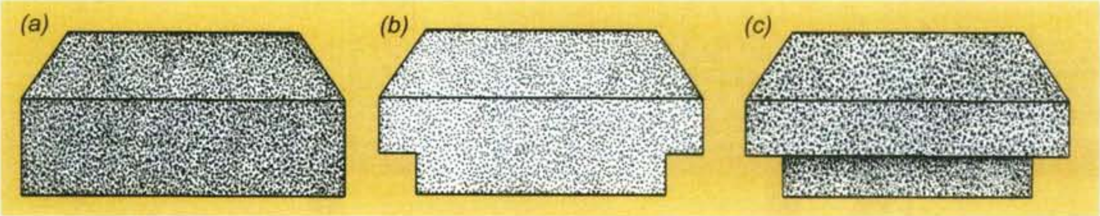
CHAPTER 15
GRANITE SURFACE PLATES

- Features of Granite Surface Plates
- Concave and Convex Granite Surface Plates
- Hand Finished Flatness
- Calibration of Granite Surface Plates
- Heavy Duty Steel Stands
- Types of Granite Plates Available

Chapter 15 Granite Surface Plates

"THE REFERENCE SURFACE"

During World War II, the traditional steel surface plates were slowly replaced by granite plates, because steel could be used for other pressed purposes, and in doing so the art and skill of creating flat surfaces by hand died away. It turned out that it was a blessing in disguise, because granite plates were superior, and the demand for steel plates fell. Today, it is not unusual to find a large number of granite plates in a factory, up to 80 or more under one roof.



See the drawing above. Of the three types presented, the two and four-ledge types, *(b)* and *(c)* respectively, are now rare. The ledges were cut to accept clamps, but now clamps are seldom used. The no-ledge plate variety *(a)* is the standard today because they can also be featured with embedded clamp down threaded holes, as in the picture at top, and are the least expensive of the three.

Features of Granite Surface Plates

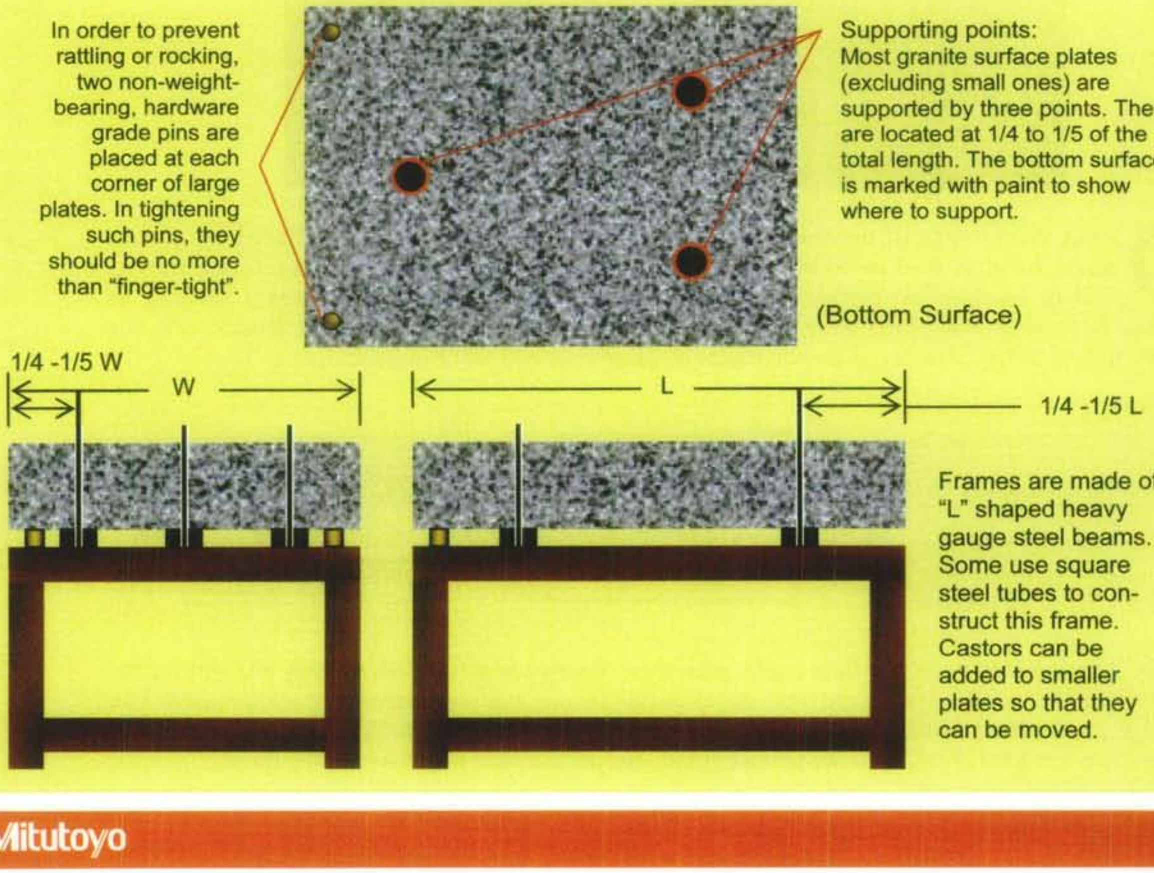
Granite Surface Plates are standard equipment in all metalworking operations and are a "must" in the quality control or temperature-controlled calibration room. The top surface of the granite plate is flat, usually within 5 µm (.0002 in) or better, depending on the size. Due to that reason, granite plates are used in most comparison measurements where gauge blocks, transfer gauges and indicators are employed.

While the top surface is very flat, it will be impossible to be "perfect". Consequently, the granite surface plates are supplied in three grades: AA, A, and B. Grade AA is the best grade, having the smallest variation in flatness. Some machinists loosely call Grade AA "Laboratory Grade", Grade A "Inspection Grade", and Grade B "shop grade".

Flatness for 12 x 12 in (300 x 300 mm) square		
Grade AA	Grade A	Grade B
.000050 in (1 µm)	.000100 in (2 µm)	.000200 in (5 µm)

Note: Numbers in ( ) are rounded.

Grade A is twice as accurate as Grade B, and similarly, Grade AA is twice as accurate as Grade A. In other words, the Grade AA is four times as accurate in flatness as Grade B. The granite plates in calibration laboratories tend to be the best grade, Grade AA. On the other hand, on the shop floor Grade B may be sufficient. It depends on the level of accuracy required.

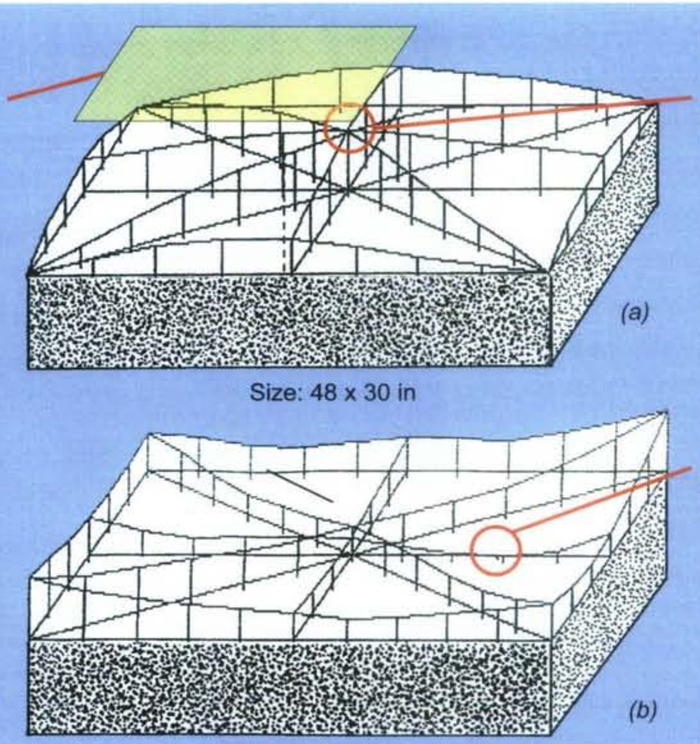


In order to prevent rattling or rocking, two non-weight-bearing, hardware grade pins are placed at each corner of large plates. In tightening such pins, they should be no more than "finger-tight".

Supporting points:
Most granite surface plates (excluding small ones) are supported by three points. They are located at 1/4 to 1/5 of the total length. The bottom surface is marked with paint to show where to support.

Frames are made of "L" shaped heavy gauge steel beams. Some use square steel tubes to construct this frame. Castors can be added to smaller plates so that they can be moved.

Concave and Convex Granite Surface Plates



Note, one quadrant of this surface plate is much better than .000245 in (6 µm), which is the maximum flatness, or Max-Min, from the lower left-hand edge to the centre of this plate.

Highest point: .000245 in (6 µm) relative to the base plane

Size: 48 x 30 in

This concave granite surface plate is much worse off than the convex plate shown above. This is not the shape the granite is finished when it was brand new.

Lowest point: -.000273 in (-7 µm) from the highest point on the plate.

Size: 60 x 36 in

Two examples are given here, one convex *(a)* and the other concave *(b)*. For a 48 x 30 inch granite plate, its flatness should be 150 µin (4µm) for Grade AA, twice more 300 µin (8 µm) for Grade A, and again twice more 600 µin (16 µm) for Grade B. Grade B, therefore, is four times poorer in flatness with respect to the best one, Grade AA. Flatness is a relative value; if the blueprint tolerance is ±.005 (±120 µm), then the Grade B will suffice unless otherwise specified.

The first the convex plate *(a)*, with a high point of .000245 in (6 µm), is not really a bad surface plate when the following factor is taken into consideration: a quadrant of this plate is much flatter than the Max-Min value suggests. It should be acceptable if comparison work is limited within this surface area.

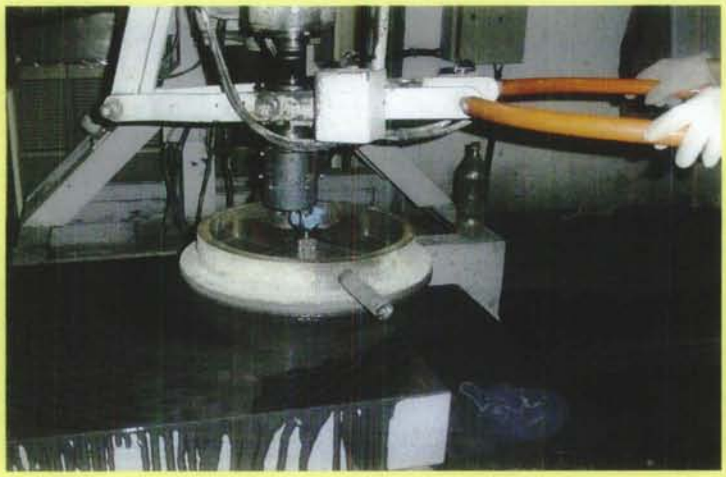
The concave surface granite plate *(b)* is poorer in flatness than *(a)*. If given a choice, one should select the convex shape *(a)* over its concave *(b)* counterpart.

While the best surface should be a flat surface — neither concave nor convex — it is hard to find a surface plate finished in a concave form *(b)* directly from the factory where the granite was finished flat. It is more common that the granite surface is slightly convex, as in the example *(a)*.

It is therefore conceivable that the first example *(a)* on top of this page is a new granite plate, while the other one *(b)* is the result of misuse. The lowest point indicated, -.000273 in (-7 µm) should be the result of continuous use on that spot. Plate *(b)* must be refinished by a qualified service person in order to produce accurate results.

Hand Finished Flatness

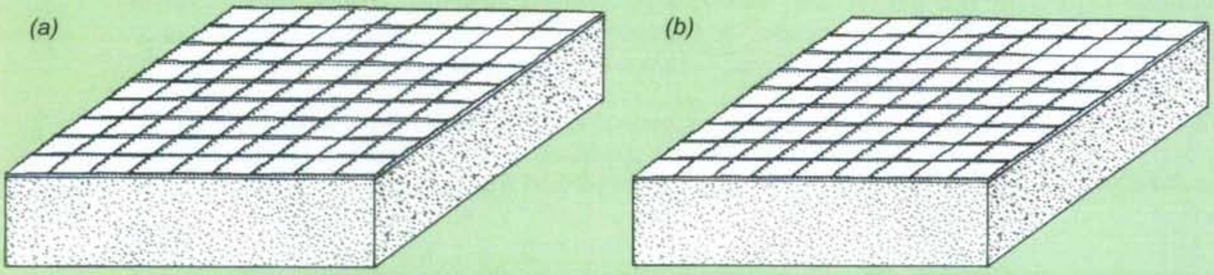
A slab of granite being rough finished by machine before hand finishing



The flatness data shown below for two 1 x 1 m square surface plates are reported by an engineer who holds a "Master of Precision" title in Mitutoyo, using a laser interferometer. The commercial-level accuracy for the flatness, Grade AA, is 100 µin (2.5 µm) for this size. The flatness data of 0.27 µm *(a)* and 0.29 µm *(b)* can be generated only by a skilled hand.

Master Kimura is such a person with this title, and the granite surface he finishes is extremely flat. He also teaches how to make 1 x 1 m granite plates flat within 1 µm (.000040 in) by hand — two and a half times better than the best Grade AA. It will take normally one week for a skilled engineer reach this goal.

1 m x 1 m Granite Surface Plates finished by a skilled senior expert: Master Kimura



(a)

(b)

Hand-finished flatness data (in micron) measured by laser interferometer

(a)

0.11	0.05	0.14	0.17	0.06	0.05	0.04	0.07	0.06	**0.00**
0.18	0.12	0.15	0.06	0.22	0.20	0.13	0.05	0.12	0.06
0.20	0.14	0.12	0.09	0.23	0.20	0.04	0.02	0.03	0.02
0.22	0.15	0.24	0.17	0.23	0.25	0.18	0.14	0.13	**-0.01**
0.19	0.08	0.20	0.20	0.19	0.20	0.18	0.20	0.19	0.05
0.11	0.09	0.22	0.18	0.25	0.25	0.23	0.13	0.25	0.11
0.04	0.16	0.19	0.17	**0.26**	0.16	0.23	0.10	0.21	0.12
0.11	0.08	0.21	0.25	0.22	0.16	0.19	0.02	0.17	0.14
0.08	0.15	0.22	0.23	0.23	0.21	0.19	0.09	0.18	0.15
0.00	0.07	0.09	0.22	0.14	0.16	0.19	0.16	0.14	0.11

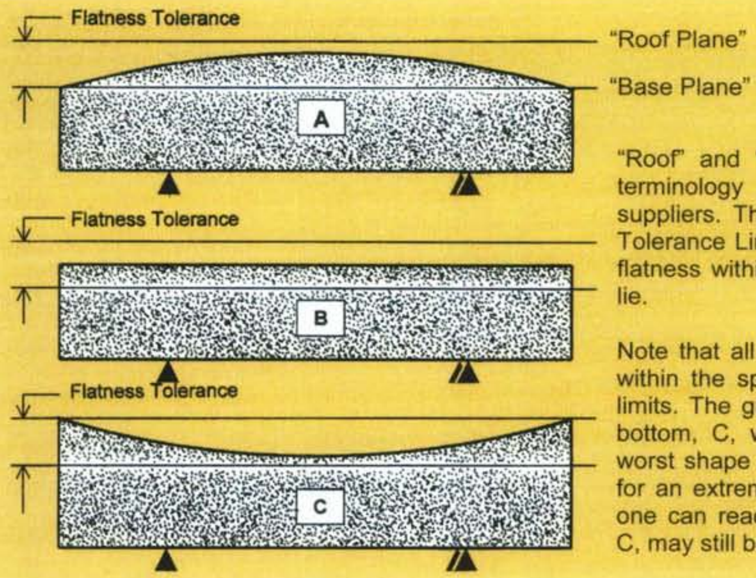
Max = 0.26 Min = -0.01 Flatness = 0.27µm (.000011 in)

(b)

0.17	0.14	0.20	0.21	0.08	0.09	0.11	0.07	0.08	**0.00**
0.17	0.17	0.22	0.15	0.22	0.21	0.21	0.09	0.15	0.04
0.17	0.21	0.20	0.14	0.22	0.17	0.12	0.07	0.12	0.02
0.21	0.28	0.27	0.22	0.27	0.19	0.27	0.14	0.24	0.01
0.21	0.21	0.25	0.21	0.22	0.16	0.23	0.21	0.25	0.04
0.16	0.19	0.28	0.20	0.27	0.22	0.28	0.14	0.27	0.13
0.15	0.27	0.20	0.14	0.27	0.19	**0.29**	0.11	**0.29**	0.16
0.15	0.25	0.18	0.27	0.27	0.16	0.20	0.04	0.26	0.20
0.10	0.23	0.16	0.26	0.27	0.18	0.20	0.06	0.23	0.18
0.00	0.16	0.09	0.25	0.12	0.14	0.21	0.13	0.15	0.17

Max = 0.29 Min = 0.00 Flatness = 0.29µm (.000012 in)

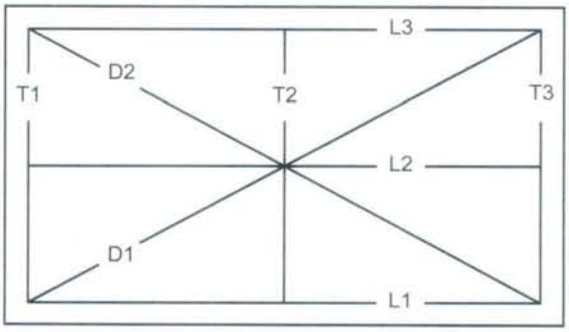
Calibration of Granite Surface Plates



"Roof" and "Base Plane" are unique terminology used by granite plate suppliers. They are Upper and Lower Tolerance Limits (UTL and LTL) of the flatness within which the surface must lie.

Note that all three examples here are within the specified flatness tolerance limits. The granite plate shown on the bottom, C, would be however in the worst shape of all. On the other hand, for an extremely large plate where no one can reach the centre, this shape, C, may still be permissible.

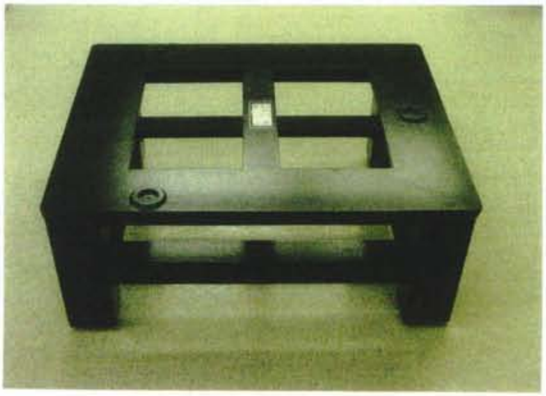
The granite surface plates can be calibrated using two different patterns: one resembles the shape of the Union Jack, as shown at right, while the other is a grid pattern shown on the facing page. The first method is the most common, although the grid pattern may provide more calibrated points, depending on its graduations.

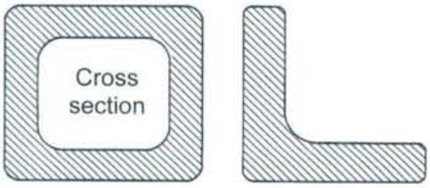


In the most common pattern, the Union Jack type, nearly 80 to 90 discrete points may be calibrated depending on the granite size. It is likely that the entire surface is covered by this method. The four corners and the edges of granite should feature either chamfered or radius. Peripheral areas near the edges are not calibrated.

Heavy Duty Steel Stands

The steel stand shown at right is a very good example of a heavy-duty steel stand. It seems as if this stand is good enough for a stack of five or even ten granite plates. Once the granite plate is installed, it likely not to be moved for a while. Thus heavy-duty steel stands like this one make sense.





Stands are made either by tubes or L-beams. They must be strong enough to sustain the weight of the granite.

Types of Granite Plates Available

Accuracy is based on the U.S. GGG-P-463C standard

Grade	**AA** Laboratory Grade			**A** Inspection Grade			**B** Shop Grade		
Size	Thick	Accuracy	Wt.	Thick	Accuracy	Wt.	Thick	Accuracy	Wt.
12 x 12	3	50	50	3	100	50	3	200	50
18 x 24	4	65	200	4	130	200	4	260	200
24 x 36	6	85	600	5	170	500	4	340	400
36 x 36	6	100	900	5	200	750	5	400	700
36 x 48	8	150	1500	6	300	1200	6	600	1200
48 x 60	12	250	3800	10	500	3150	8	1000	2530
60 x 60	14	250	5500	12	500	4800	10	1000	4000
60 x 72	14	350	6600	12	700	5750	10	1400	4900
72 x 72	14	400	8000	12	800	7000	10	1600	5700
72 x 120	16	700	15070	14	1400	13400	12	2800	11400

Size and thickness are in inches. Weight is shown in pounds. Accuracy of flatness is stated in micro-inches or millionths of an inch. For example, 100 = .000100 in. and 65 = .000065 in.

There is a product called granite plate cleaner sold at industrial distributors, though denatured alcohol would be equally good for cleaning. While this is not so critical, it is important to note that granite expands or contracts as temperature changes.

In selecting a granite plate, flatness, not colour, is important, although some prefer a darker plate, because small workpieces placed on the plate can be easily found. There are several colours available, 4 of which are featured here.

When choosing a plate, the surface, when touched by hand, should feel as smooth as a slice of cheese. No pin-holes and no crevasses should be obvious on the surface.

Index

Acknowledgements

I was fortunate to be surrounded by a number of experts in the field of Metrology. Many of my mentors, in the United States and abroad, unselfishly passed their knowledge to me, simply because I was the only one around. It is largely their knowledge that is expressed in this Handbook. I deeply thank my colleagues and associates, past and present, for their encouragement and patience. Although it is customary to name all contributors on this page, I respectfully decline to make a list for fear of including some and excluding others.

When I was just another kid on the block, and no one was in the office to give me the answer, I often looked into Dr. Francis Farago's excellent and definitive book '*Fundamentals of Metrology*' (First Edition 1970, Industry Press, NY) provided me with insightful information. Also, '*Fundamentals of Dimensional Metrology*' by Ted Bush (Dalmer Publication) gave me practical ideas. I was also impressed by Wayne Moore's absolutely magnificent and therefore rather expensive hardcover '*Foundation of Mechanical Accuracy*', published by Moore Specialty Tool in Bridgeport, Connecticut.

I hope this Handbook will shed another light onto the subjects left untouched by the aforementioned authors and others. In fact, many of the technologies covered here came after they had finished their manuscripts. Some of the data furnished in this book are supplied from internal sources.

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