Fundamentals of Dimensional Metrology

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Agenda

- Metrology Fundamentals
  - History, metre & micron, precision & accuracy, source of error and basic principles.
- Geometric Design and Tolerancing
  - Rules, material modifiers, datum and features.
- Inspection Methods
  - Methods for GD&T inspection, gauge design & gauges, transfer Instruments, virtual bodies, thread nomenclature.
- Co-ordinate Measuring Machine (CMM)
  - Good practice, limitations and applications.
- Introduction to the Measurement of Surface Texture
- Manufacturing Process Capabilities

What is Metrology?

- The Science of Measurement.
- Understanding of measurement of the quality and quantity.
- Evidence of traceability and accuracy.
- Repeatability, reproducibility, reliability.
- Understanding the uncertainty.

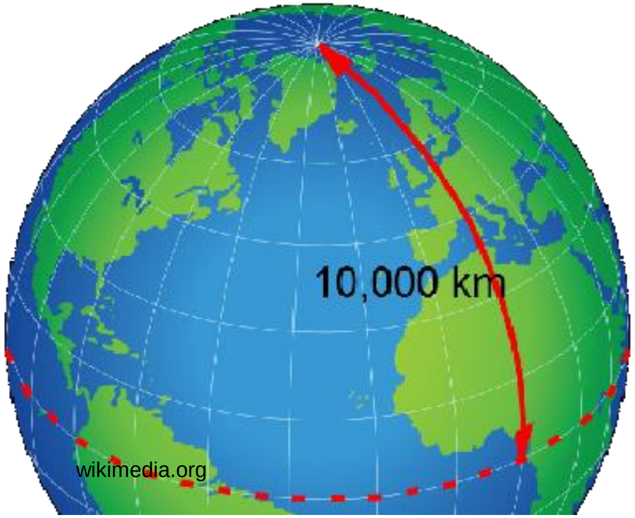
Origins of Metrology

- The **cubit** believed to be the first unit of measurement 1550-1069 BC.
- Length based on the distance from the elbow to the tip of the middle finger (52cm).
- Division: 7 palms or 28 fingers.

wikimedia.org

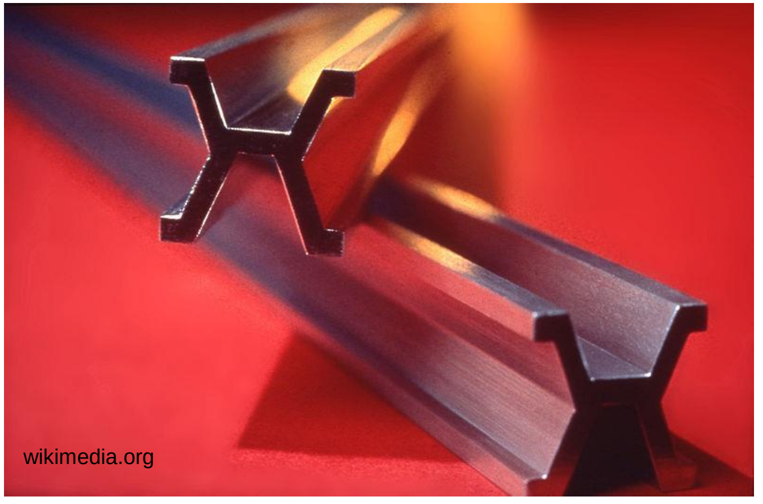
The Metre

- Developed after the French Revolution (1789), replace the old units of measure that were associated with royalty .
- Originally intended to be one ten-millionth of the distance from the Earth's equator to the North Pole (at sea level) distance along the meridian running from the North Pole to the equator through Dunkirk, France and Barcelona, Spain.



The Metre

- French scientists worked nearly six years to complete the task in November 1798.
- Platinum-iridium bar as the physical replica of the metre.
- The surveyors made an error of about two miles. The error has not been corrected.



Dimensional Measurement

- The National Measurement Institutes are responsible for ensuring consistency and traceability.
- The metre is now determined by the distance that the light from an iodine-stabilised helium neon laser travels through a vacuum in 1/299,792,458 of a second.
- The second has been defined to be: the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

International System of Units (SI)

Quantity	Unit	Symbol	Definition
Mass	kilogram	kg	The mass of the international prototype of the kilogram (made from platinum-iridium alloy and kept in Paris in a carefully controlled environment.
Time	second	s	The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
Length	metre	m	The length of the path travelled by light in a vacuum during a time interval of 1/299,792,458 of a second.
Thermodynamic temperature	kelvin	K	The fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Electric current	ampere	A	That current which, if maintained in two straight parallel conductors of infinite length, of negligible cross-section and placed one metre apart in a vacuum, would produce between these conductors a force of 2×10^{-7} newton per metre.
Luminous intensity	candela	cd	The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{-12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.
Amount of substance	mole	mol	The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

Derived Units - Combined SI

Quantity	Derived unit	Symbol	Unit of quantity
Area	square metre	-	m^2
Volume	cubic metre	-	m^3
Speed	metre per second	-	$m.s^{-1}$
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg.m.s^{-2}$
Pressure	pascal	Pa	$kg.m^{-1}.s^{-2}$
Energy, work	joule	J	$kg.m^2.s^{-2}$
Power	watt	W	$kg.m^2.s^{-3}$
Potential difference	volt	V	$kg.m^2.s^{-3}.A^{-1}$
Electrical resistance	ohm	Ω	$kg.m^2.s^{-3}.A^{-2}$
Magnetic flux density	tesla	T	$kg.s^{-2}.A^{-1}$

Orders of Magnitude

Prefix	Symbol	Decimal	Power of 10
yotta	Y	1000000000000000000000000	10^{24}
zetta	Z	1000000000000000000000	10^{21}
exa	E	1000000000000000000	10^{18}
peta	P	1000000000000000	10^{15}
tera	T	1000000000000	10^{12}
giga	G	1000000000	10^{9}
mega	M	1000000	10^{6}
kilo	k	1000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	µ	0.000001	10^{-6}
nano	n	0.000000001	10^{-9}
pico	p	0.000000000001	10^{-12}
femto	f	0.000000000000001	10^{-15}
atto	a	0.000000000000000001	10^{-18}
zepto	z	0.000000000000000000001	10^{-21}
yocto	y	0.000000000000000000000001	10^{-24}

How big is a micron?

Measurement Process

- Measurement is the process to obtain the value of a quantity.
- The quantity being determined is called the measurand (physical object being measured).
- Measurement Instrument is used to generate a value for the measurand.
- Value of the measurand is stated in SI unit.

True Value and Measured Value

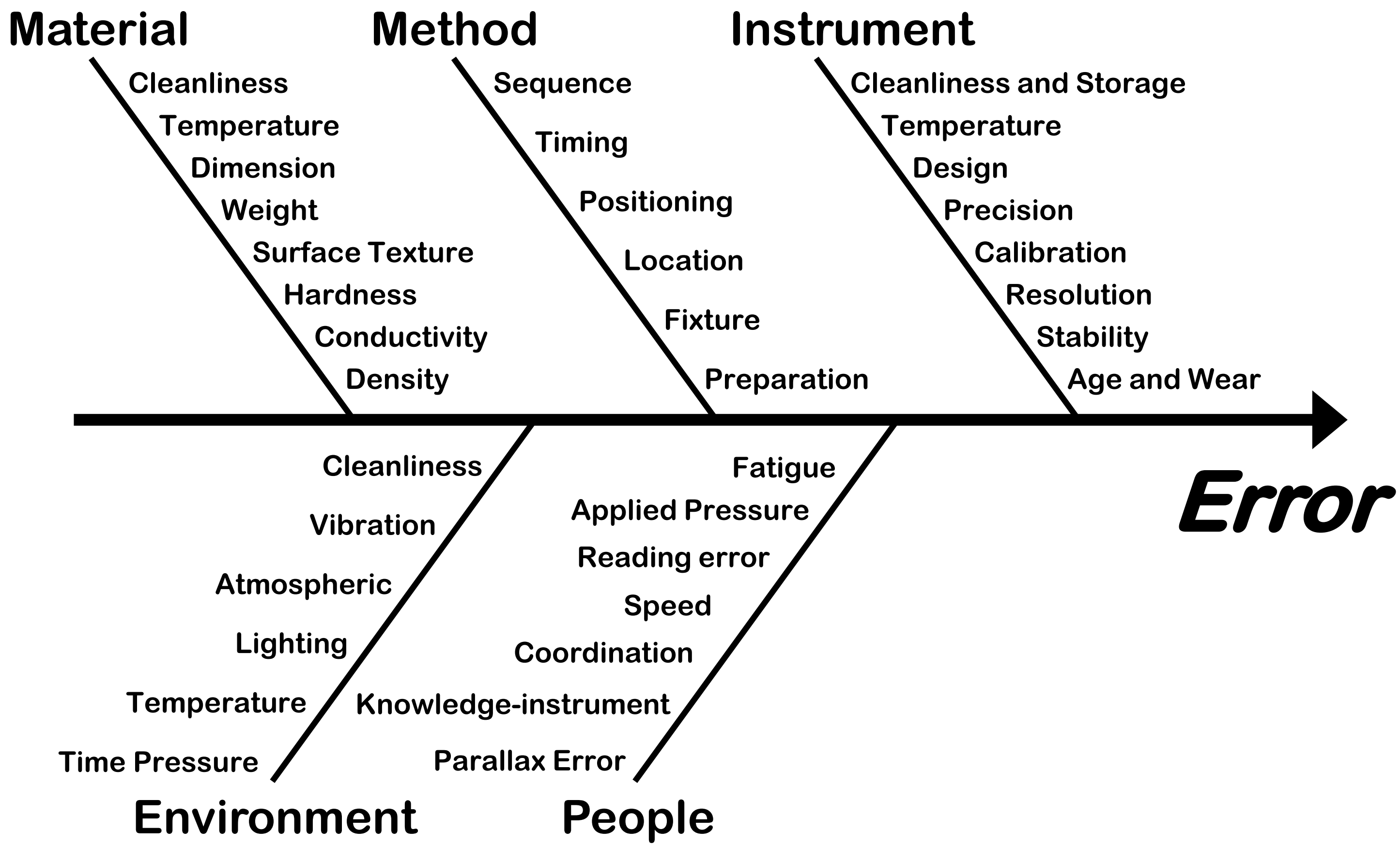
- Measurement Instruments are not perfect and the displayed value is not the true value.
- Therefore measurement are only an estimate.
- Knowing the precision of an instrument is important and selection should be based on the application.

If one of these items was dimensionally incorrect by 2µm would it matter?

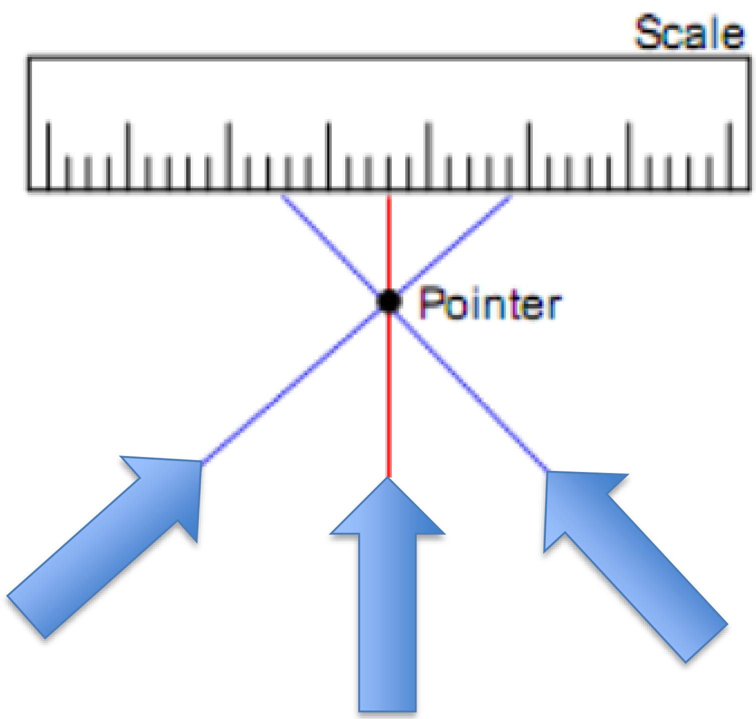
Factors that influence measurement

- Fixture
- Lighting
- Parallax Error
- Age and Wear
- Cleanliness
- Reading error
- Temperature
- Surface Texture
- Calibration
- Applied Pressure
- Knowledge-instrument

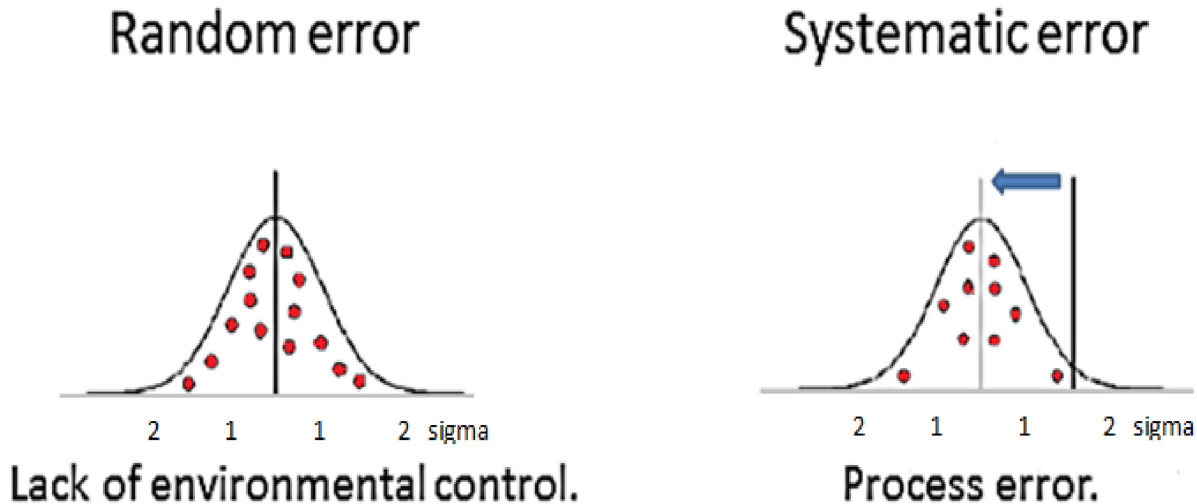
Factors that influence measurement



Parallax Error



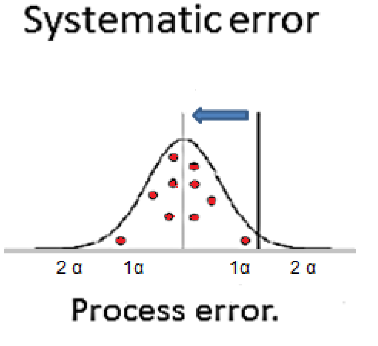
Two Types of Error



- Multiple measurements will always form a standard “Gaussian” distribution curve
- Systematic error or Bias is often corrected by calibration.
- Other components of the measurement system, for example, applied pressure, temperature, fixtures etc. can create a systematic error and a bias in measured values.

What is calibration?

- Comparison of a measurement instrument against a standard of higher accuracy (gauge block).
- Purpose is to detect, correct and document the instrument performance and uncertainty.
- Instruments may drift over time making recalibration a necessity.
- Most common calibration is to correct systematic error.

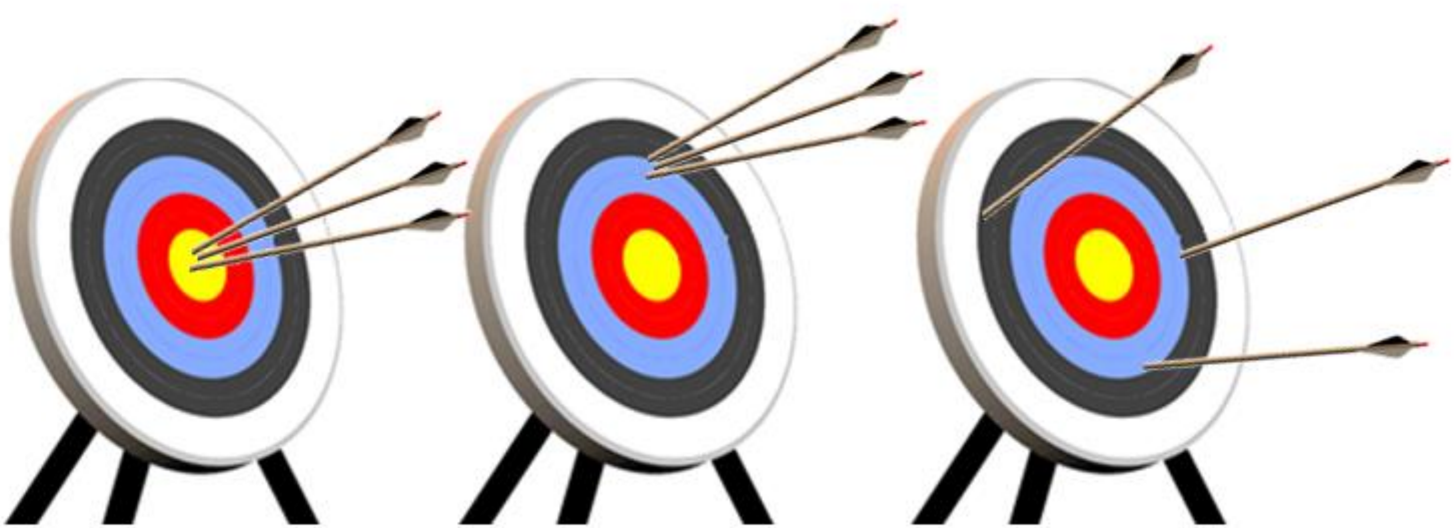


How often should we calibrate?

- No standard is available to control this.
- Things to consider:
  - How stable is the instrument over time.
  - How often is the instrument used.
  - The quantity and value of the components.
  - The environment and storage.
  - The manufacturers specification for the instrument.

- Monitor instruments and record the calibration, use this information to determine the calibration interval.

Accuracy and Precision



Accurate and Precise	Precise but not Accurate	Not Accurate and not Precise

Accurate measurement system has small systematic error, precise measurement system has small random error.

Key points to remember

- Temperature.
- Applied pressure.
- Parallax error.
- Calibration.
- Storage.
- Measurement process.
- Cleanliness.
- Experience.

Temperature Compensation

Calculation:

$$L_{20} = L_T + (20 - T)\,\alpha\, L_T$$

- L_T = Length measured.
- T = Ambient temperature when measurement taken.
- α = The coefficient of expansion of the measurand.

Traceability

- Prove a traceable and unbroken route to the national standards body.
- Uncertainty of a measured value is determined by the unbroken chain.
- NPL in the UK.

National Standards accurate to 0.001%

Calibration Laboratories- UKAS accurate to 0.01%

Standards - gauge blocks and setting rings accurate to 0.05%

Inspection instruments accurate to 0.1%

Process instrumentation and product accurate to 1%

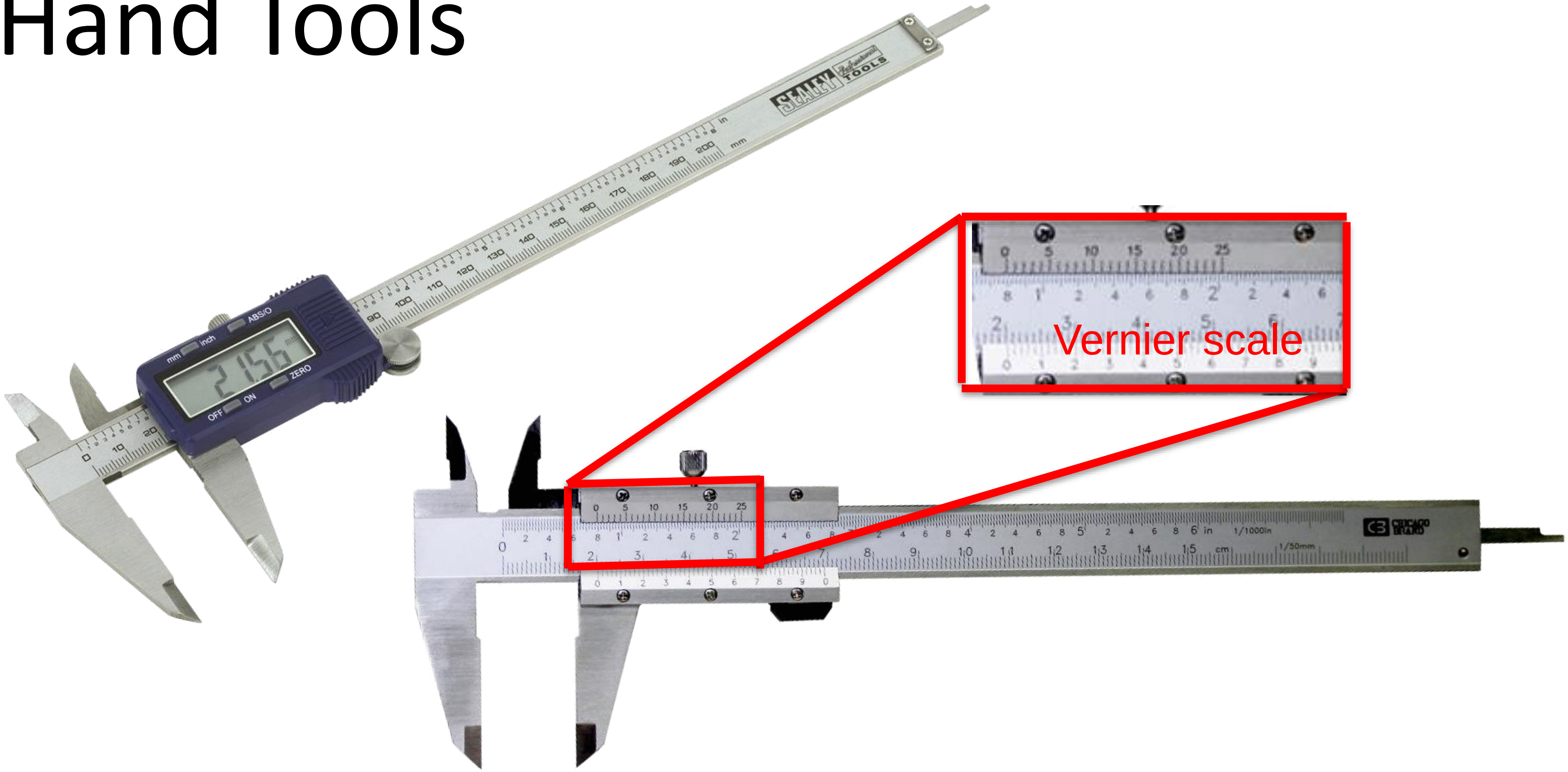
With each step towards the National measurement standards bodies we look for an artefact that has a precision of at least 10 times greater accuracy.

Transfer Standards

- Gauge blocks are our most accurate standard available in our engineering practice.

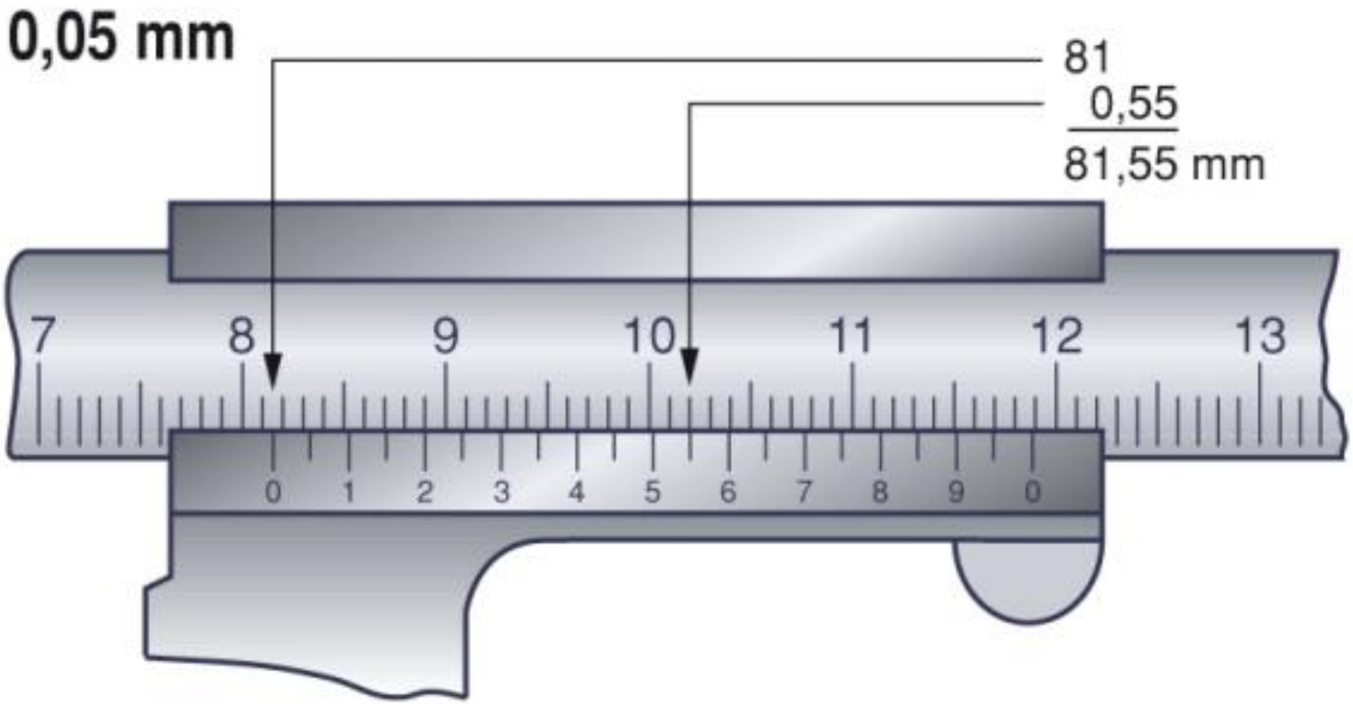
Length Over	–	Up to	Accuracy at 20°C (µm) Grade K*	Grade 0	Grade 1	Grade 2
0.5	–	10mm	±0.20	±0.12	±0.20	±0.45
10	–	25mm	±0.30	±0.14	±0.30	±0.60
25	–	50mm	±0.40	±0.20	±0.40	±0.80
50	–	75mm	±0.50	±0.25	±0.50	±1.00
75	–	100mm	±0.60	±0.30	±0.60	±1.20
100	–	150mm	±0.80	±0.40	±0.80	±1.60
150	–	200mm	±1.00	±0.50	±1.00	±2.00
200	–	250mm	±1.20	±0.60	±1.20	±2.40
250	–	300mm	±1.40	±0.70	±1.40	±2.80
300	–	400mm	±1.80	±0.90	±1.80	±3.60
400	–	500mm	±2.20	±1.10	±2.20	±4.40
500	–	600mm	±2.60	±1.30	±2.60	±5.00
600	–	700mm	±3.00	±1.50	±3.00	±6.00

Hand Tools



Who knows what this is?

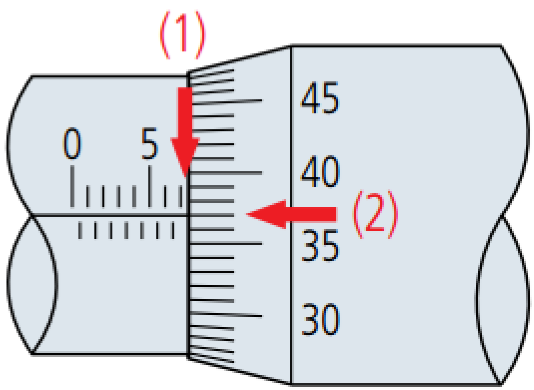
How to read a Vernier scale



Courtesy of Tesa

How to read a Vernier scale

- **Micrometer with standard scale (graduation: 0.01 mm)**



(1) Sleeve scale reading	7.00 mm
(2) Thimble scale reading	0.37 mm
Micrometer reading	7.37 mm

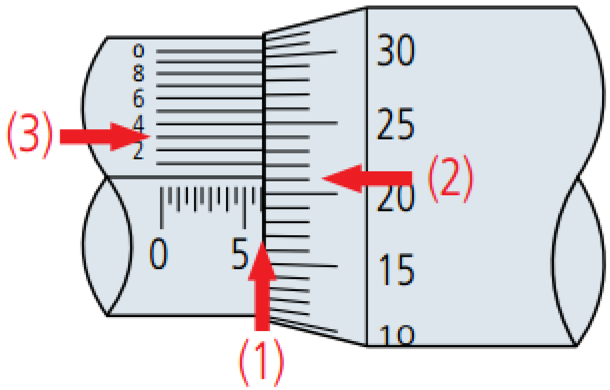
Note: 0.37 mm (2) is read from the thimble scale where it intersects the index line.

The thimble scale can be read directly to 0.01 mm, as shown above, but may also be estimated to 0.001 mm when the lines are nearly coincident because the line thickness is 1/5 of the spacing between them.

Mitutoyo Quick guide to Measurement

How to read a Vernier scale

- Micrometer with vernier scale (graduation: 0.001 mm)



(1) Sleeve scale reading	6.000 mm
(2) Thimble scale reading	0.210 mm
(3) Vernier scale reading	0.003 mm
Micrometer reading	6.213 mm

Note: 0.21 mm (2) is read at the position where the index line is between two graduations (21 and 22 in this case). 0.003 mm (3) is read at the position where one of the vernier graduations aligns with one of the thimble graduations.

Mitutoyo Quick guide to Measurement

Which has the greatest precision for measuring adimensions less than 50mm?

Digital caliper

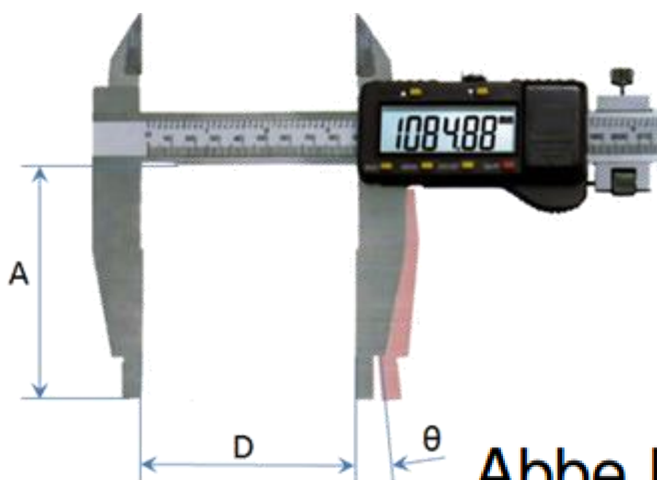
CMM Workshop

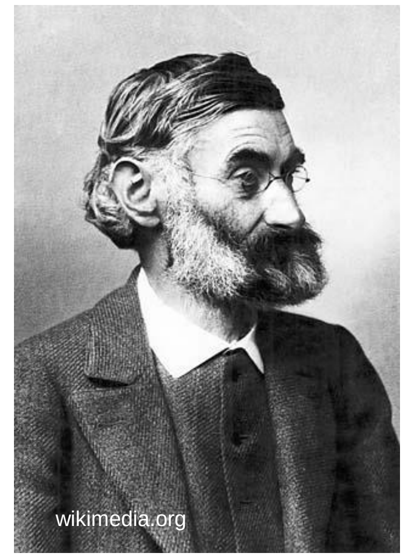
Digital Height Gauge

Micrometer

Abbe’s Principle 1840-1905

“ The axis or line of measurement should coincide with the axis of measuring instrument or line of the measuring scale”





Abbe Error (E) = $A*\sin(\theta)$

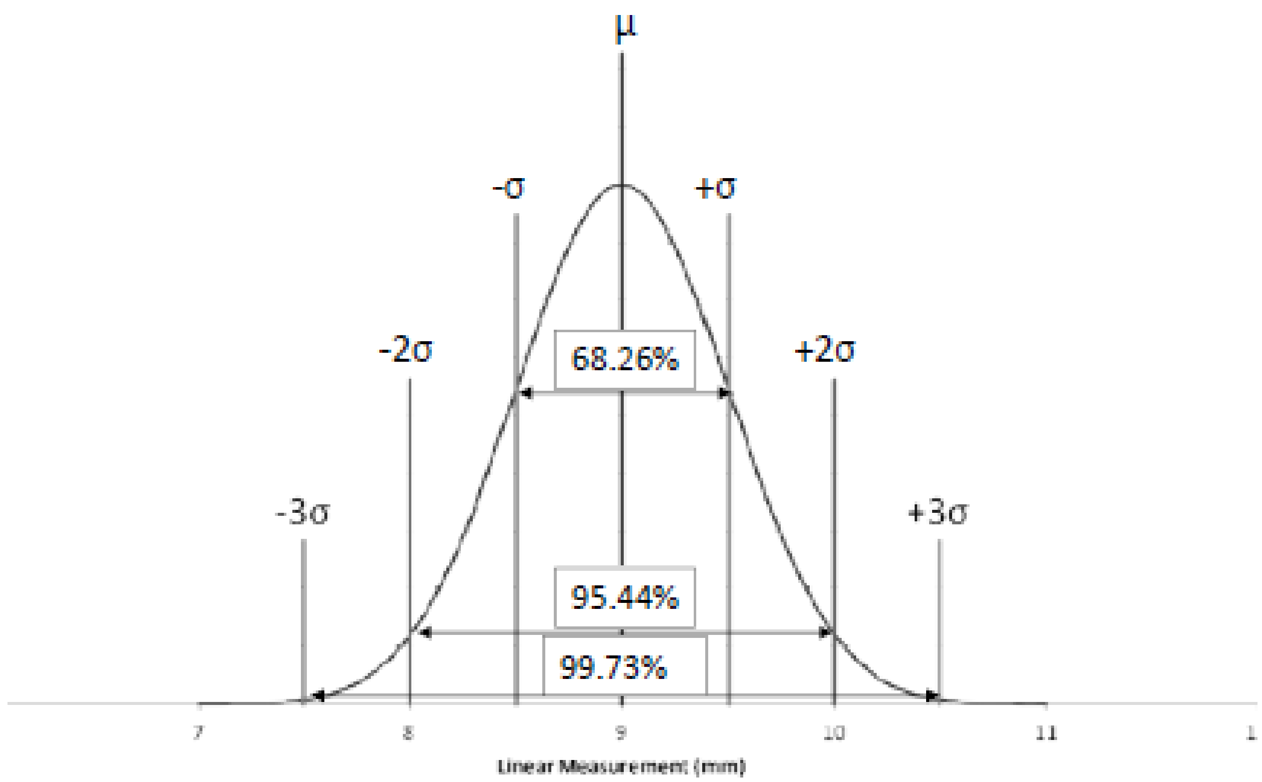
Micrometer Variations

Instrument Resolution

- 0.4560” 11.582mm.
- Check the instrument specification.
- ***Manufacturers specification.***
- ***Resolution 0.0005“ (0.001mm).***
- ***Accuracy +/-0.002“ (0.05mm).***
- ***At 2 sigma.***

Six sigma (3 standard distributions)

- A six sigma process is one in which 99.73% are statistically expected to be in the stated uncertainty.



Calculating the standard deviation

- Calculating the standard deviation of a set of measurements informs us how individual measurements differ from the average of the set.

$$\sigma = \sqrt{\frac{\sum(xi - \bar{x})^2}{N - 1}}$$

$\sum$ Means the "sum of".

xi = Sum of the values in the data set.

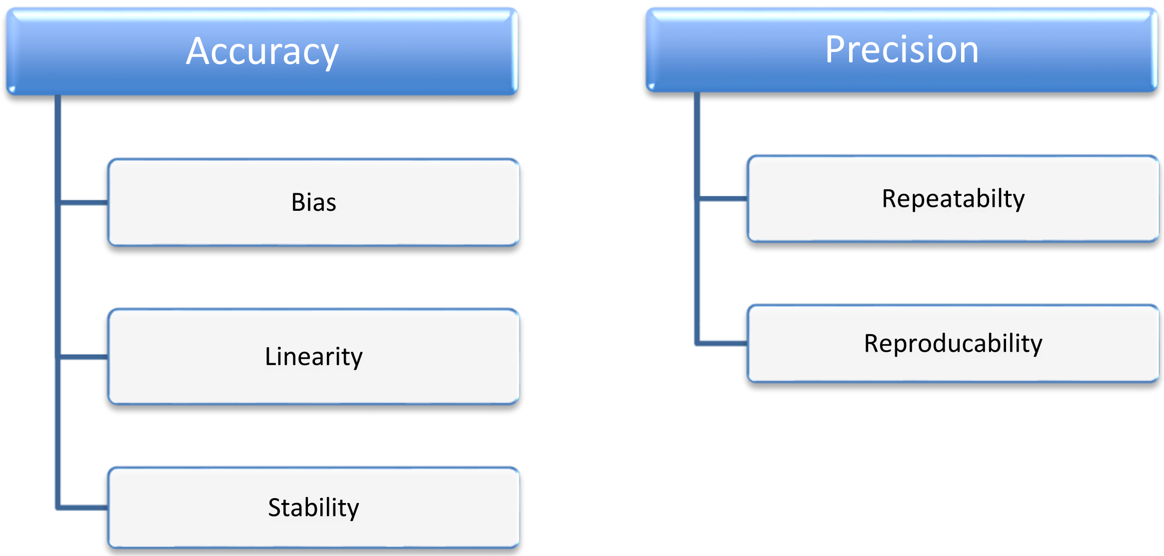
$\bar{x}$ = Mean of all the values in the data set.

N = Number of values in the data set.

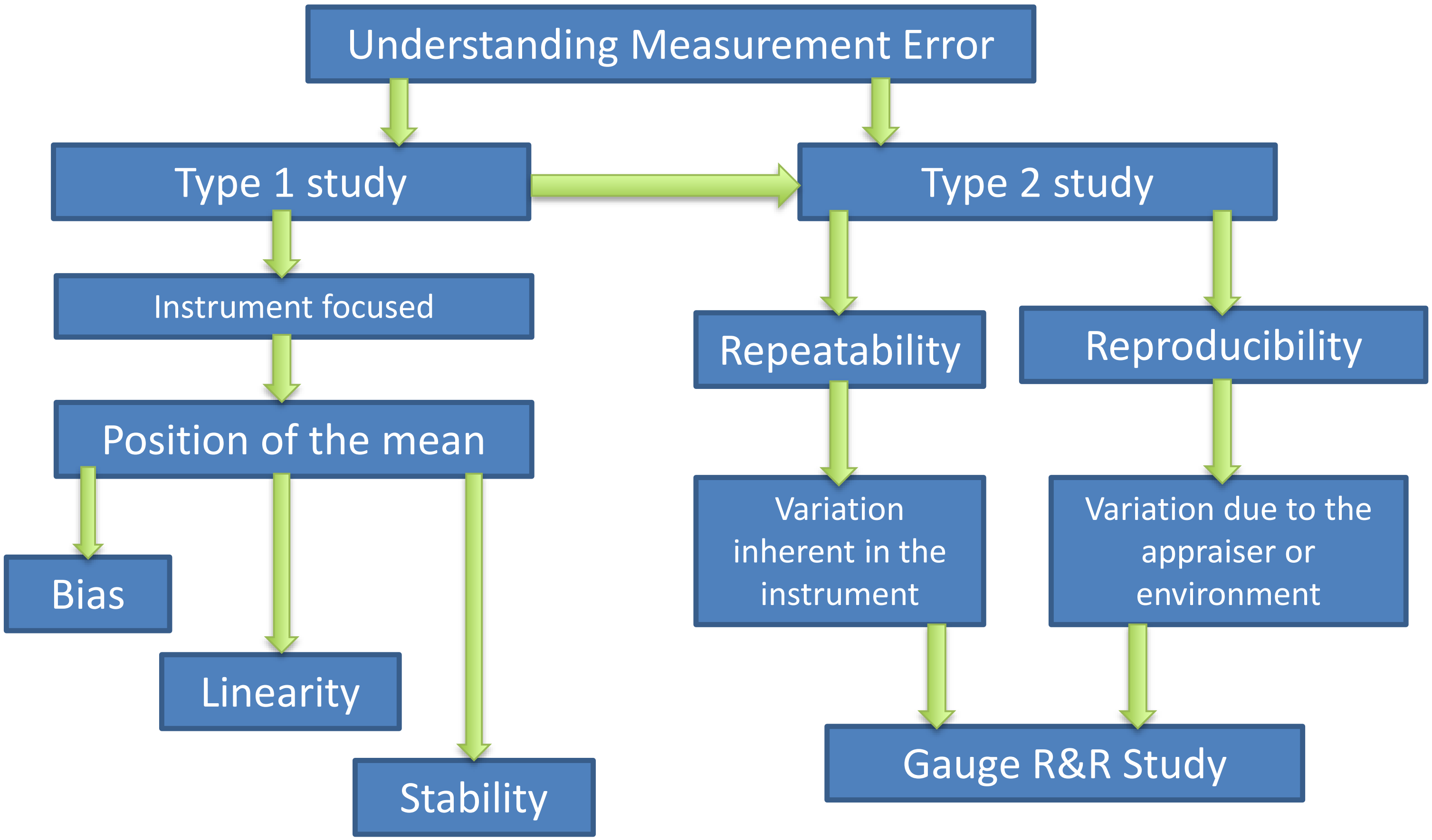
Measurement Strategy

- Selection of features on the work piece to be measured.
- Understand the work piece datum feature and its relationship to the coordinate system.
- Selection of work piece orientation and fixtures.
- Selection and qualification of measurement instruments is critical remember the 10% rule.
- Understand how to use the instrument, especially the scale.
- Check the calibration status and the instrument for damage.
- Clean the instrument before use in particular the measurement faces.
- Take more than one measurement and review the recorded values; do they make sense.

Measurement System Analysis



Measurement System Analysis



Type 1 Study (MSA)

- Instrument focused
- Bias as a percentage of the tolerance

$$\text{Bias\%} = 100 \times \left(\frac{\text{Mean of Measured Values} - \text{Reference Measurement}}{\text{Feature Tolerance}} \right)$$

The Mean of Measured Values is normally represented by $\bar{x}$ *and will be for the remainder of the chapter.*

Type 1 Study (MSA)

- The equation for CgK comprises the equations for Cg and bias

$$\mathrm{CgK} = \frac{\big((\mathrm{K} \div 200) \times \mathrm{FeatureTolerance}\big) - (\bar{\mathrm{x}}\ - \mathrm{Reference\ Measurement})}{\mathrm{L} \times \sigma}$$

It is common to set a benchmark for the two metrics Cg and CgK of 1.33. A value of 1.33 indicates the study variation is within 75% of the available feature tolerance.

Type 1 Study (MSA)

- Cg metric is a measure of the system's repeatability

$$\mathrm{Cg} = \frac{(\mathrm{K} \div 100) \times \text{Feature Tolerance}}{\mathrm{L} \times \sigma}$$

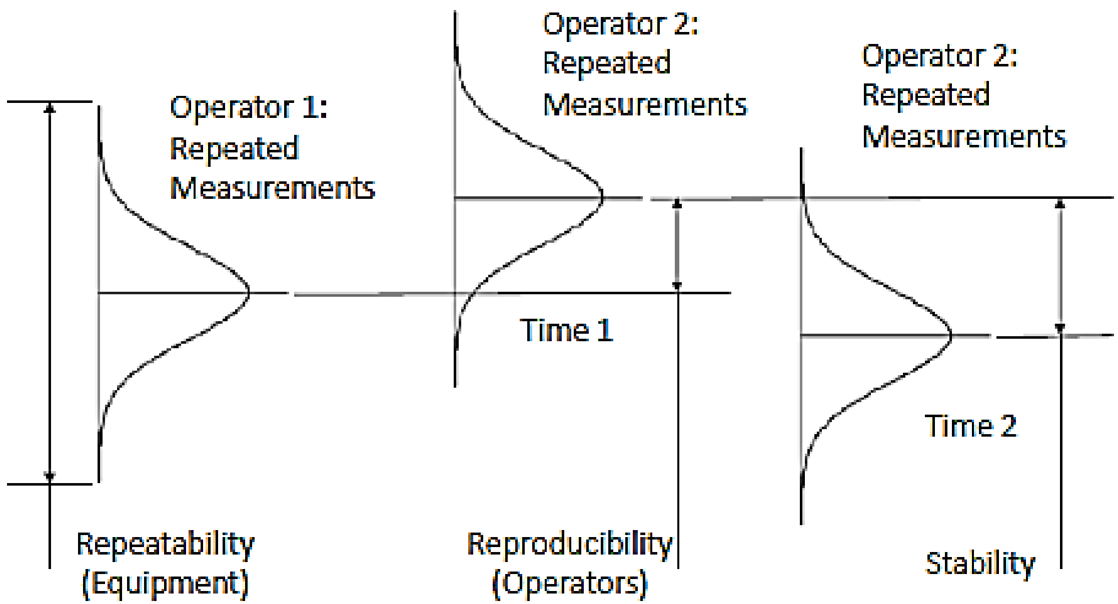
K = the percentage of the Feature Tolerance, 20% is commonly used although 10% for high precision component may be advisable.
L = the number of standard deviations, 3 is commonly used in this calculation.
σ = the standard deviation.

Type 2 Study (MSA)

Gauge R&R – Gauge Repeatability and Reproducibility.

- Repeatability of the instrument recorded measurement.
- Reproducibility of a measurement; influence of operator.

  - 10 Parts.
  - 3 Appraisers.
  - 3 Repeats.



Type 2 Study (MSA)

Three main sources of variation:

- Variation in the components.
- Operator performing the measurements.
- Instrument used to perform the measurement.

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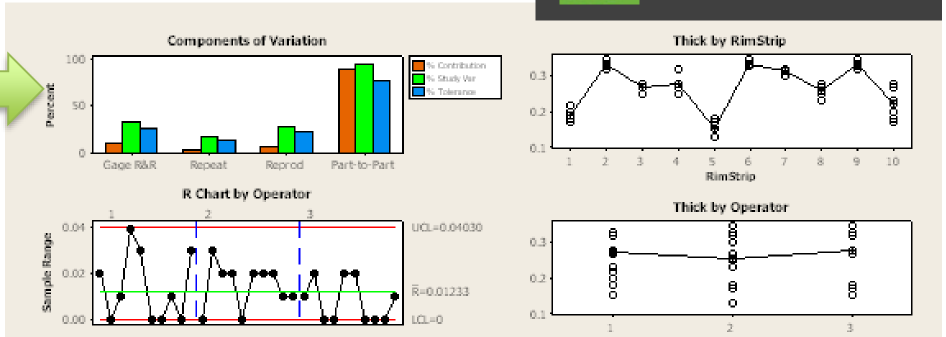
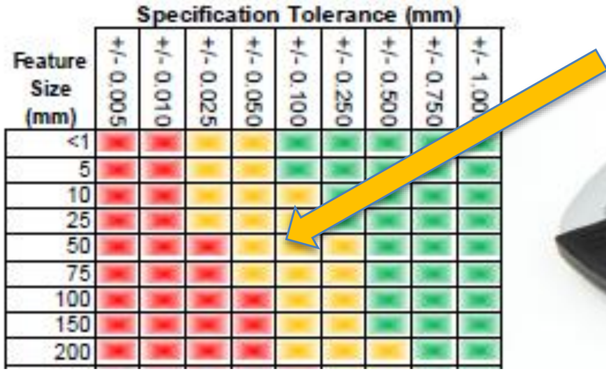
Part to Part should be the significant component of variation.



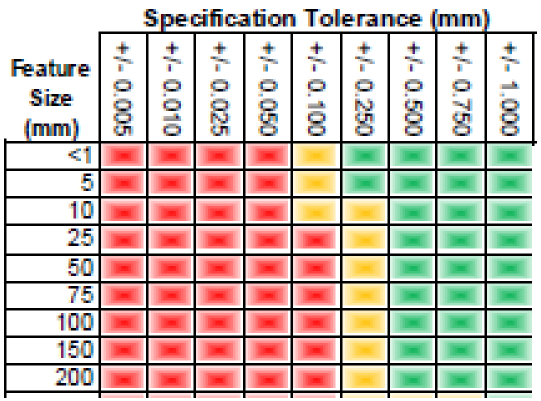
Uncertainty Budget

Ref No.	Component of Uncertainty	Distribution Type	Expanded Uncertainty U	Divisor k	Standard Uncertainty u $u = U \div k$
$u1$	Instrument calibration	Normal	0.050	2	0.025
$u2$	Resolution	Rectangular	0.010	1.73	0.006
$u3$	Temperature	Rectangular	0.012	1.73	0.007
$u4$	Fixture	Normal	0.020	2	0.010
$u5$	Repeatability	Normal	0.100	2	0.050
Combined uncertainty $uc = \sqrt{u1^2 + u2^2 + u3^2 + u4^2 + \ldots etc.}$					0.058
Combined expanded uncertainty $(k = 2)$ for a 95% confidence level $= uc \times k$					0.115

Hand Tool Capability



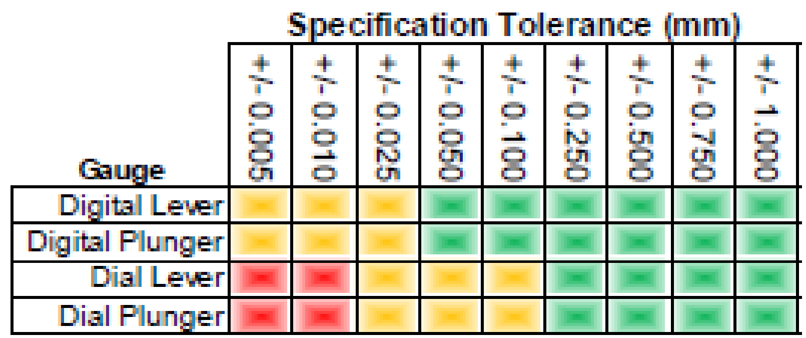
Experienced and suitably qualified person



The chart only accounts for the instrument not the entire measurement system or environment.
Reference Rolls Royce Guide to Dimensional Measurement Equipment Version 3.1.

DTI Capability

- Subject to the effects of Hysteresis (drift due to backlash).
- Cosine error is a major issue when using lever indicators.



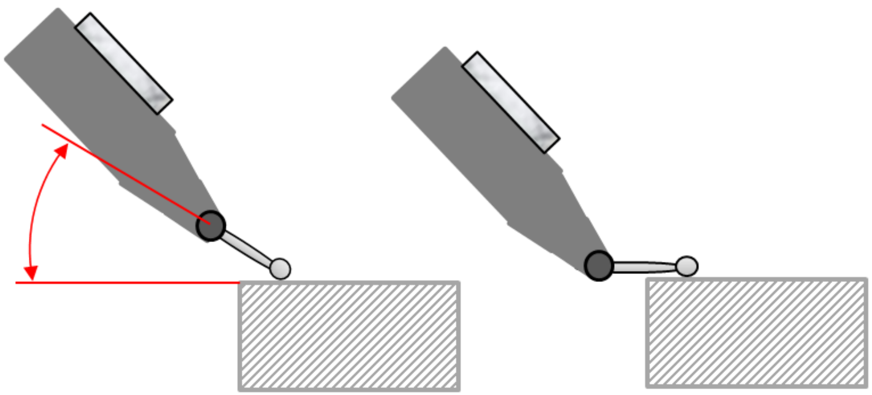
Gauge	Specification Tolerance (mm) +/- 0.005	+/- 0.010	+/- 0.025	+/- 0.050	+/- 0.100	+/- 0.250	+/- 0.500	+/- 0.750	+/- 1.000
Digital Lever									
Digital Plunger									
Dial Lever									
Dial Plunger									

Table 21 - Indicators Capability Chart

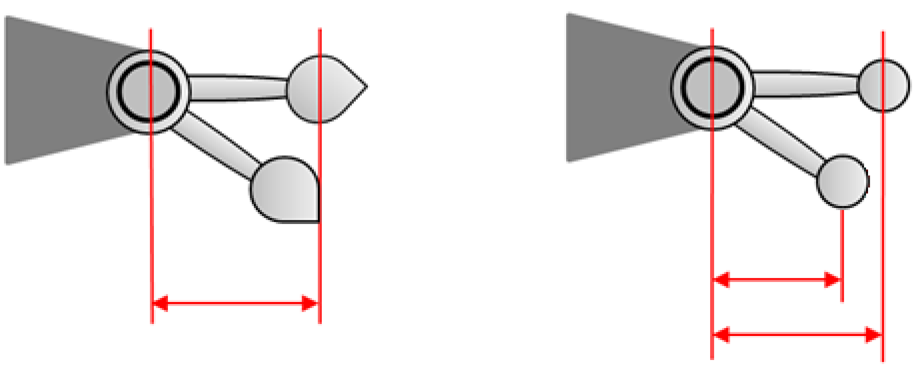
Reference Rolls Royce Guide to Dimensional Measurement Equipment Version 3.1.

Cosine Error

Angle A	Correction Factor
10°	.985
20°	.940
30°	.866
40°	.766
50°	.643
60°	.500



Angle 40° Indicator Reading 0.05
Correction Factor .940 (cos 40°)
0.05 x .940 = 0.038



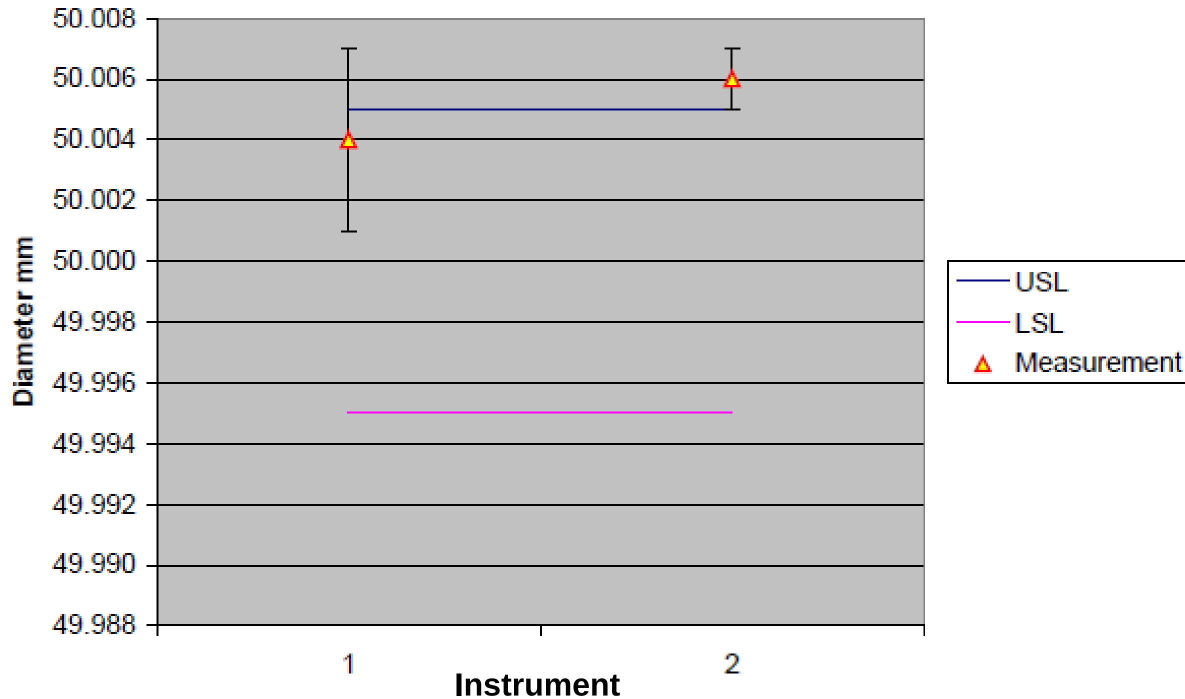
Pear shaped contact lever
eliminates cosine error up to 36°

Extracts from.. NPL Good Practice in Dimensional Metrology (No. 80)

Hole design tolerance:
50 mm ± 0.005 mm

Instrument 1
- Micrometer
- ± 0.003 mm

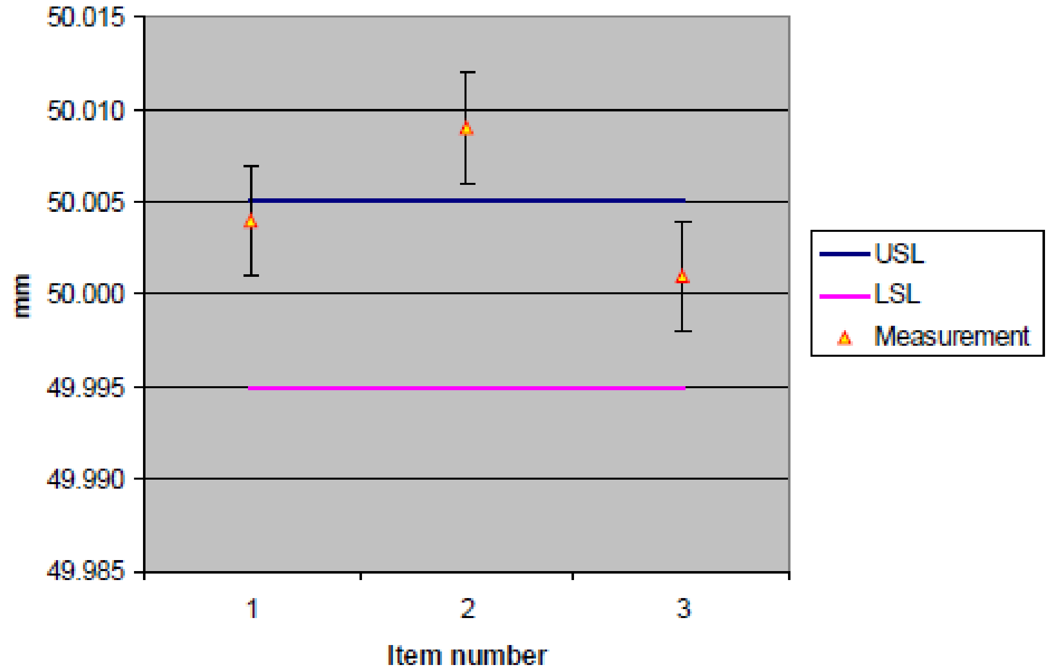
Instrument 2
- Bore comparator
- ± 0.001 mm



Remember: *As a general rule the measurement uncertainty of the equipment should be no greater than ten percent of the tolerance band*

Extracts from.. NPL Good Practice in Dimensional Metrology (No. 80)

*Conformance with a specification can only be proven when the **result of a measurement (complete with a statement on uncertainty)** falls within tolerance zone*



***Possible outcomes** - measurement of 3 items:*

1. *Neither conformance nor non-conformance with a specification can be proven*
2. *Non-conformance is proven*
3. *Conformance is proven*

Extracts from.. NPL Good Practice in Dimensional Metrology (No. 80)

Allow for the uncertainty of the measuring device by reducing the size of the acceptance band

Example process with a 25 µm specified tolerance range

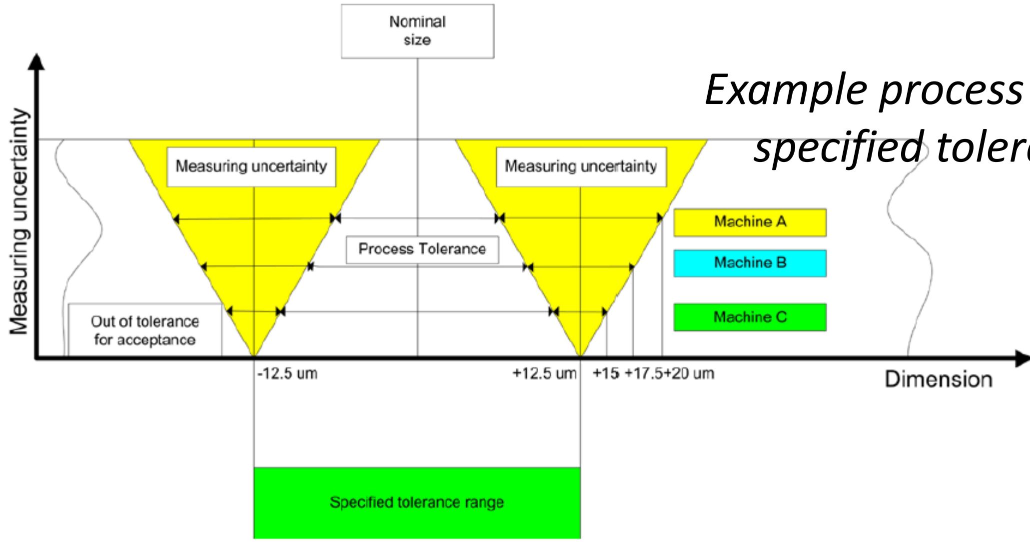
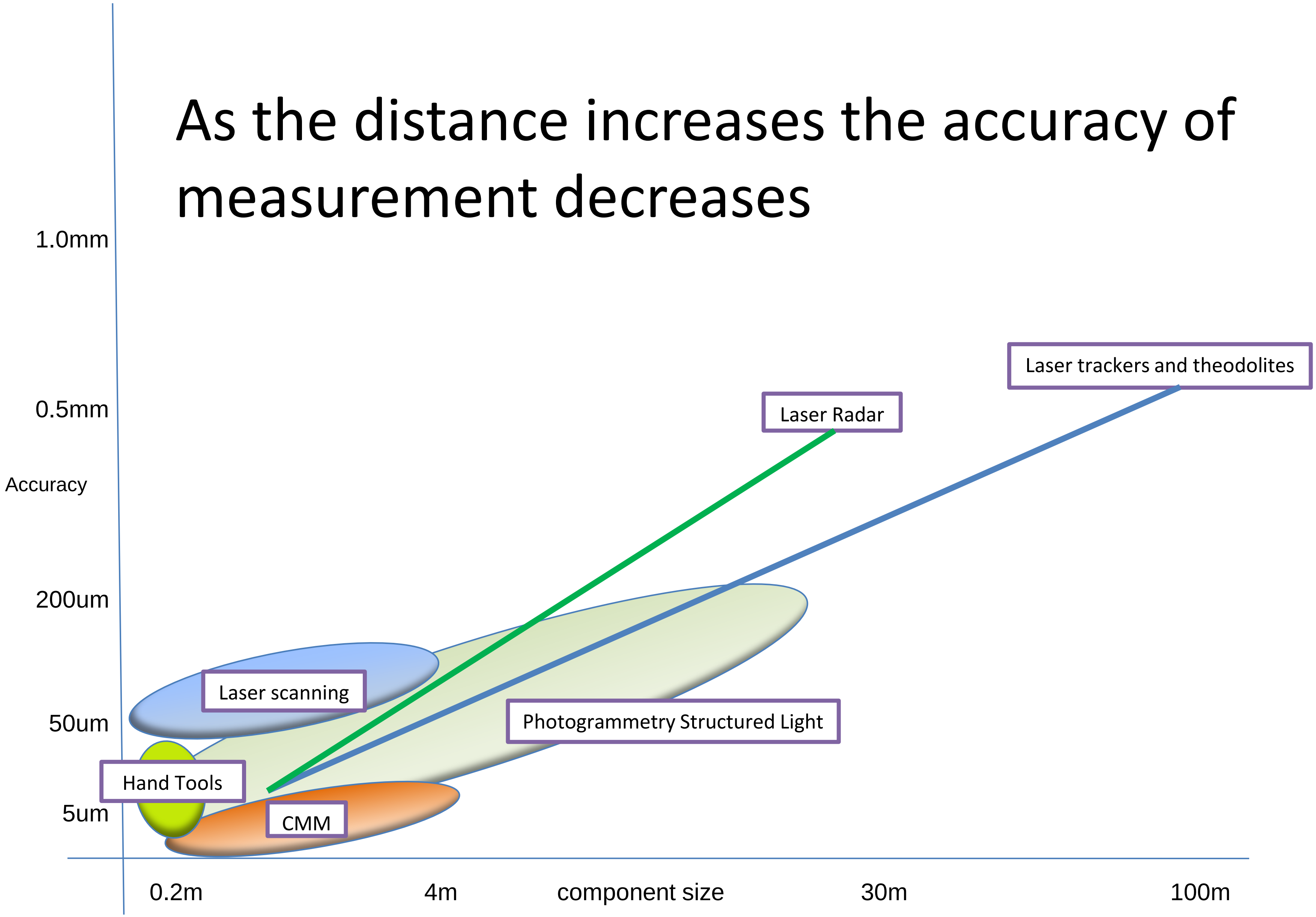


Figure 16 Impact of measurement uncertainty

Table 2 Impact of measurement uncertainty

	Measuring uncertainty	Specified tolerance range	For production		For customer
			Available tolerance	Costs	Available tolerance
Machine A	7.5 µm	25 µm	10 µm	High	40 µm
Machine B	5 µm	25 µm	15 µm	Average	35 µm
Machine C	2.5 µm	25 µm	20 µm	Low	30 µm

As the distance increases the accuracy of measurement decreases



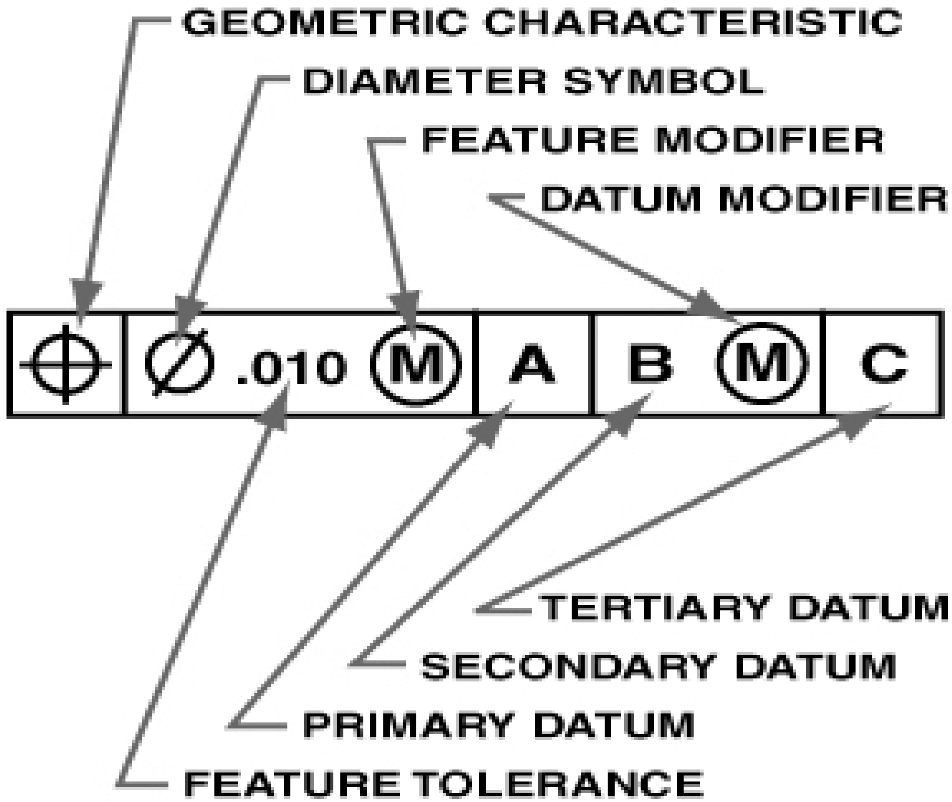
GD&T Geometric Dimensioning and Tolerances

ASME and ISO

This following information is based on ASME Y14.5M and correct at time of creation. Please always refer to the current standard.

TYPE OF TOLERANCE	CHARACTERISTIC	SYMBOL	DATUM REFERENCE
FORM	STRAIGHTNESS	⏤	INDIVIDUAL
	FLATNESS	⏥	
	CIRCULARITY (ROUNDNESS)	○	
	CYLINDRICITY	⌭	
PROFILE	PROFILE OF A LINE	⌒	INDIVIDUAL OR RELATED
	PROFILE OF A SURFACE	⌓	
ORIENTATION	ANGULARITY	∠	RELATED
	PERPENDICULARITY	⊥	
	PARALLELISM	∥	
LOCATION	POSITION	⌖	
	CONCENTRICITY	◎	
	SYMMETRY	⌯	
RUNOUT	CIRCULAR RUNOUT	↗	
	TOTAL RUNOUT	⌰	

Feature Control Frame

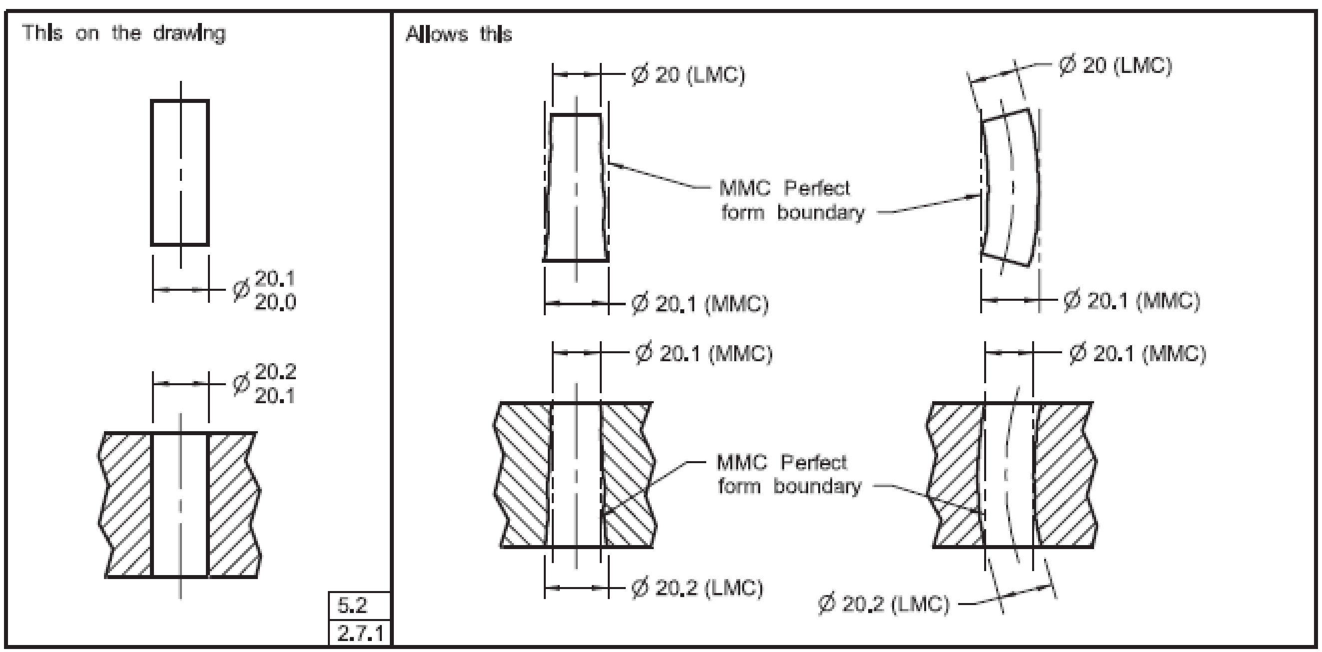


Variations of Form Rule #1: Envelope Principle

Taylor Principle

The surface or surfaces of a regular feature of size shall not extend beyond a boundary (envelope) of perfect form at MMC. This boundary is the true geometric form represented by the drawing. No variation in form is permitted if the regular feature of size is produced at its MMC limit of size unless a straightness or flatness tolerance is associated with the size dimension or the Independency symbol is applied.

Fig. 2-6 Extreme Variations of Form Allowed by a Size Tolerance



ASME Y14.5M

Regardless of Feature Size (RFS)

Regardless of feature size (RFS): indicates a geometric tolerance applies at any increment of size of the actual mating envelope of the feature of size.

⌖	0.004 Ⓢ	A Ⓢ

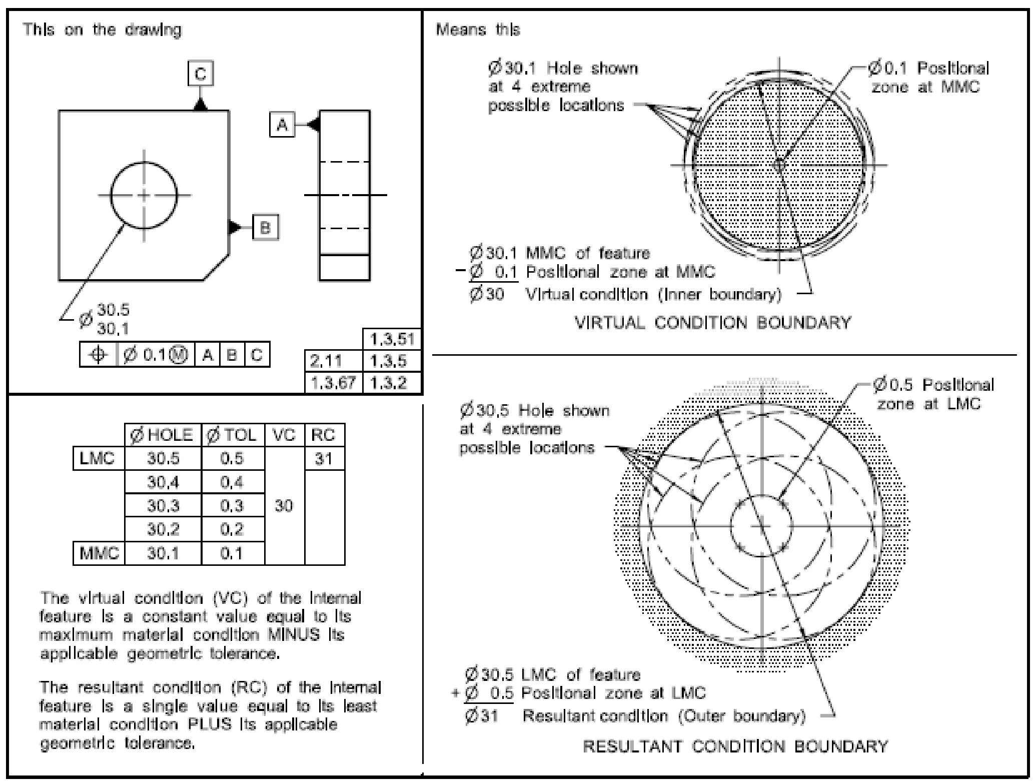
This is the default condition and it is no longer necessary to state this in the feature control frame.

ASME Y14.5M

Virtual Condition

A constant boundary generated by the collective effects of a considered feature of the size’s specified MMC or LMC and the geometric tolerance for that material condition.

Fig. 2-12 Virtual and Resultant Condition Boundaries Using MMC Concept — Internal Feature



	Ø HOLE	Ø TOL	VC	RC
LMC	30.5	0.5		31
	30.4	0.4		
	30.3	0.3	30	
	30.2	0.2		
MMC	30.1	0.1		

ASME Y14.5M

Material Condition Modifiers

In GD&T, **maximum material condition (MMC)** refers to a feature-of-size that contains the greatest amount of material, yet remains within its tolerance zone. Some examples of MMC include:

- Largest pin diameter or smallest hole size.

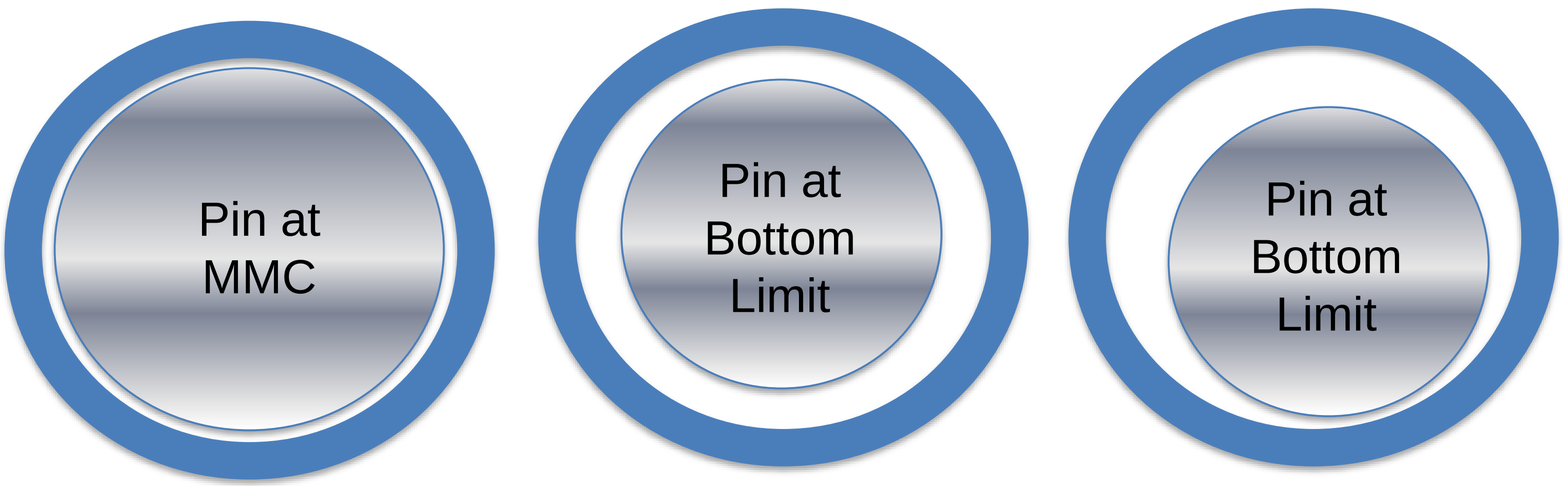
In contrast, **least material condition (LMC)** refers to a feature of size containing the least amount of material, yet remains within its tolerance zone.

- Smallest pin diameter or largest hole size .

The MMC and LMC symbols are, respectively, the letter M or L inside of a circle. M L

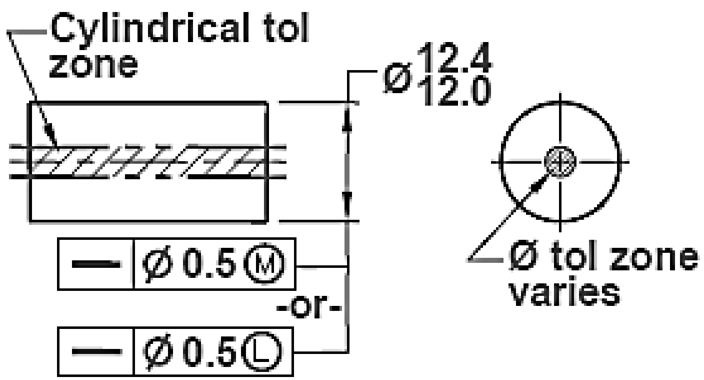
MMC example of Bonus Tolerance

Bonus tolerance can be applied to pin position and assembly is still possible when the pin is not at maximum size.



Additional positional tolerance and assembly is still possible

MMC example of Bonus Tolerance



MMC

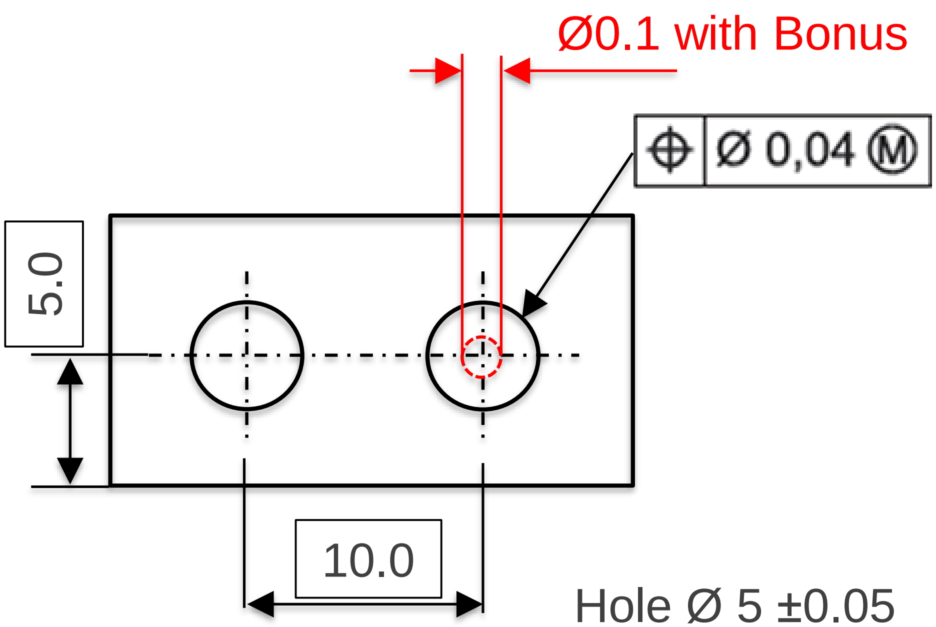
Feature Diameter	Diameter Tolerance Zone
12.4 MMC	0.5
12.3	0.6
12.2	0.7
12.1	0.8
12.0 LMC	0.9

LMC

Feature Diameter	Diameter Tolerance Zone
12.0 LMC	0.5
12.1	0.6
12.2	0.7
12.3	0.8
12.4 MMC	0.9

MMC example of Bonus Tolerance

MMC LMC applied to Feature



Actual hole sizes

= Ø5.01

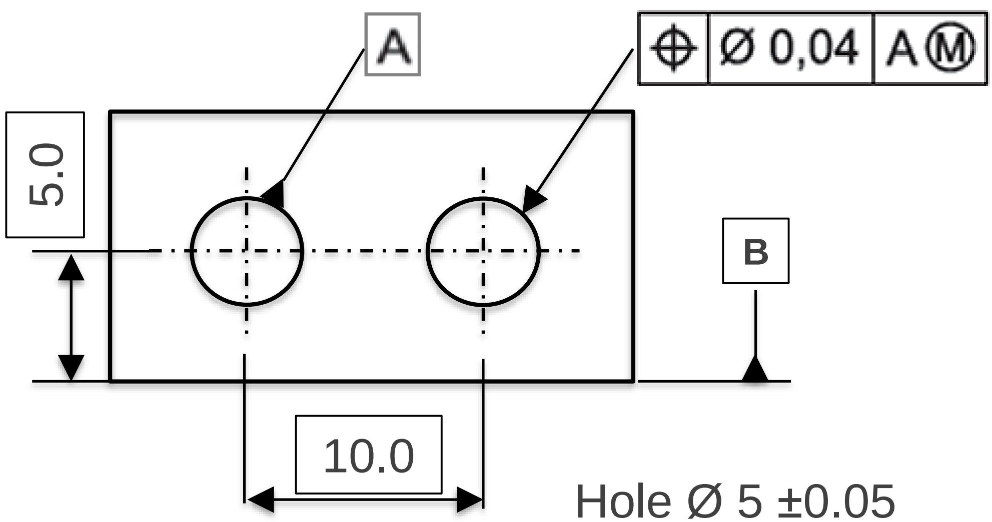
Datum MMC = Ø4.95

5.01 - 4.95 = 0.06 Bonus

Ø0.1 with Bonus is the new positional tolerance.

MMC example of Bonus Tolerance

MMC applied to Datum



Actual hole sizes

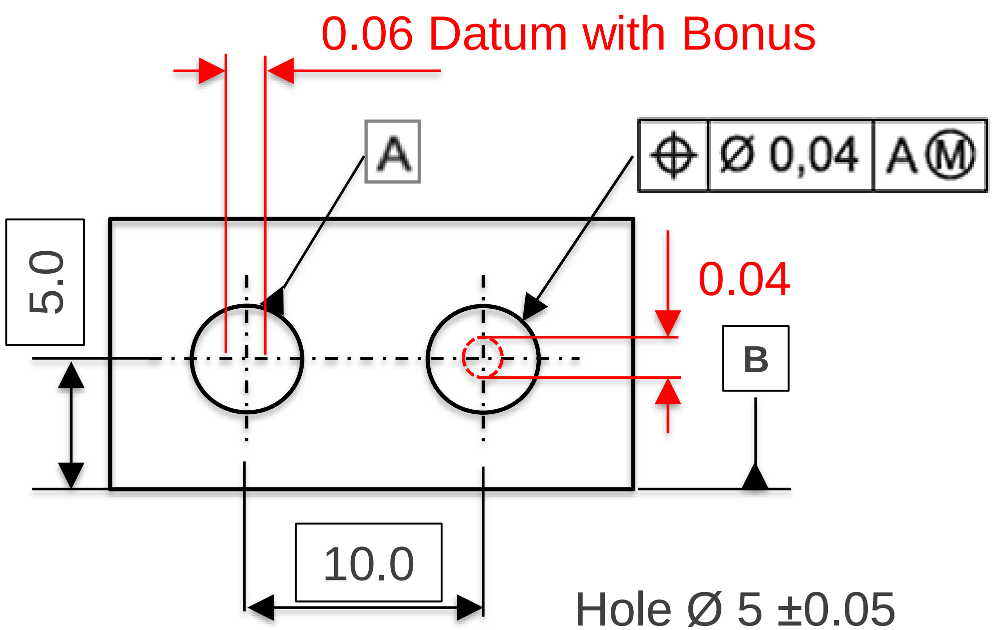
= Ø5.01

Datum MMC = Ø4.95

5.01 - 4.95 = 0.06 Bonus

MMC example of Bonus Tolerance

MMC applied to Datum

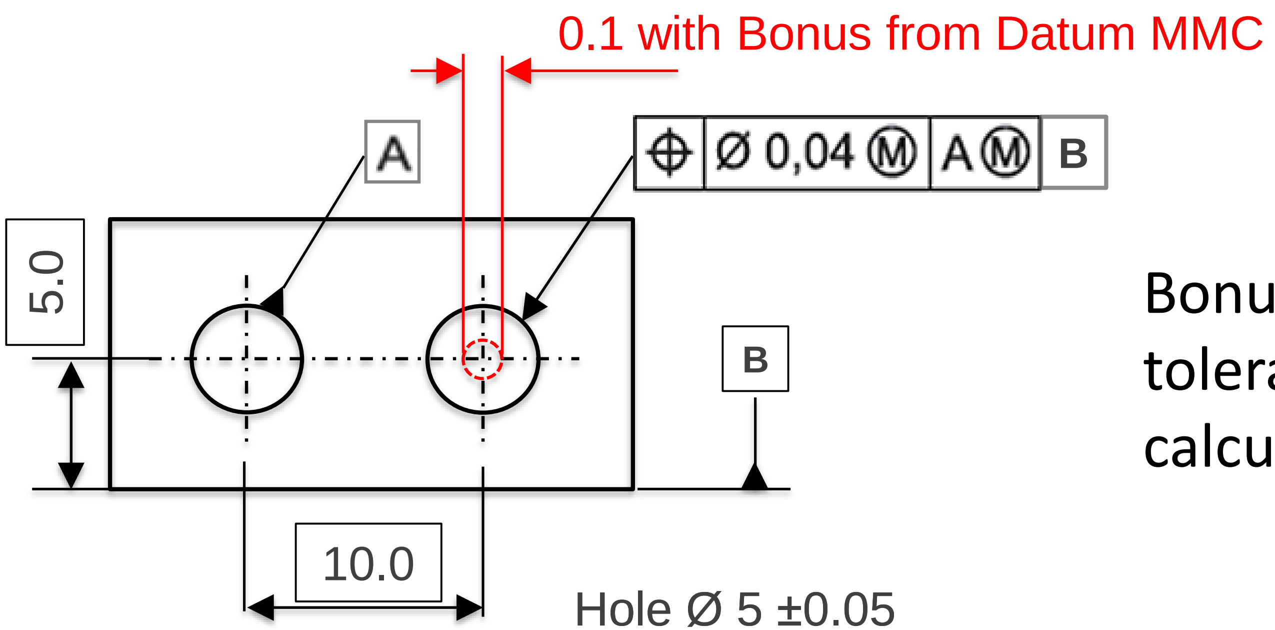


However, MMC is only applied horizontal direction.

Vertical direction is still controlled by Datum B the original Positional Tolerance of 0.04mm.

MMC example of Bonus Tolerance

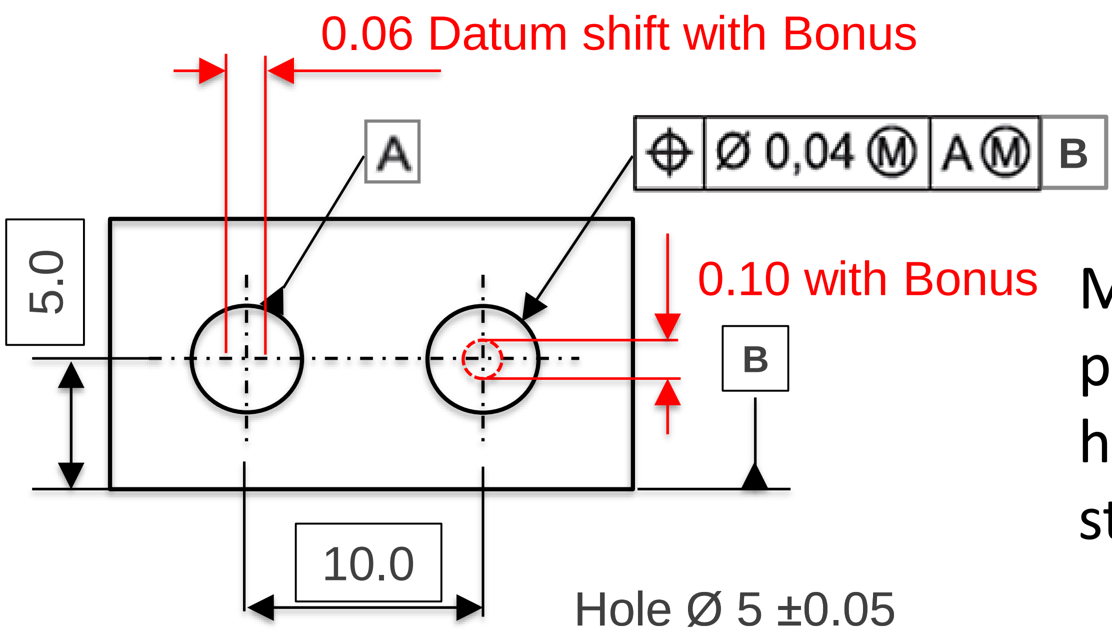
MMC applied to Datum and Feature



Bonus positional tolerance as previously calculated.

MMC example of Bonus Tolerance

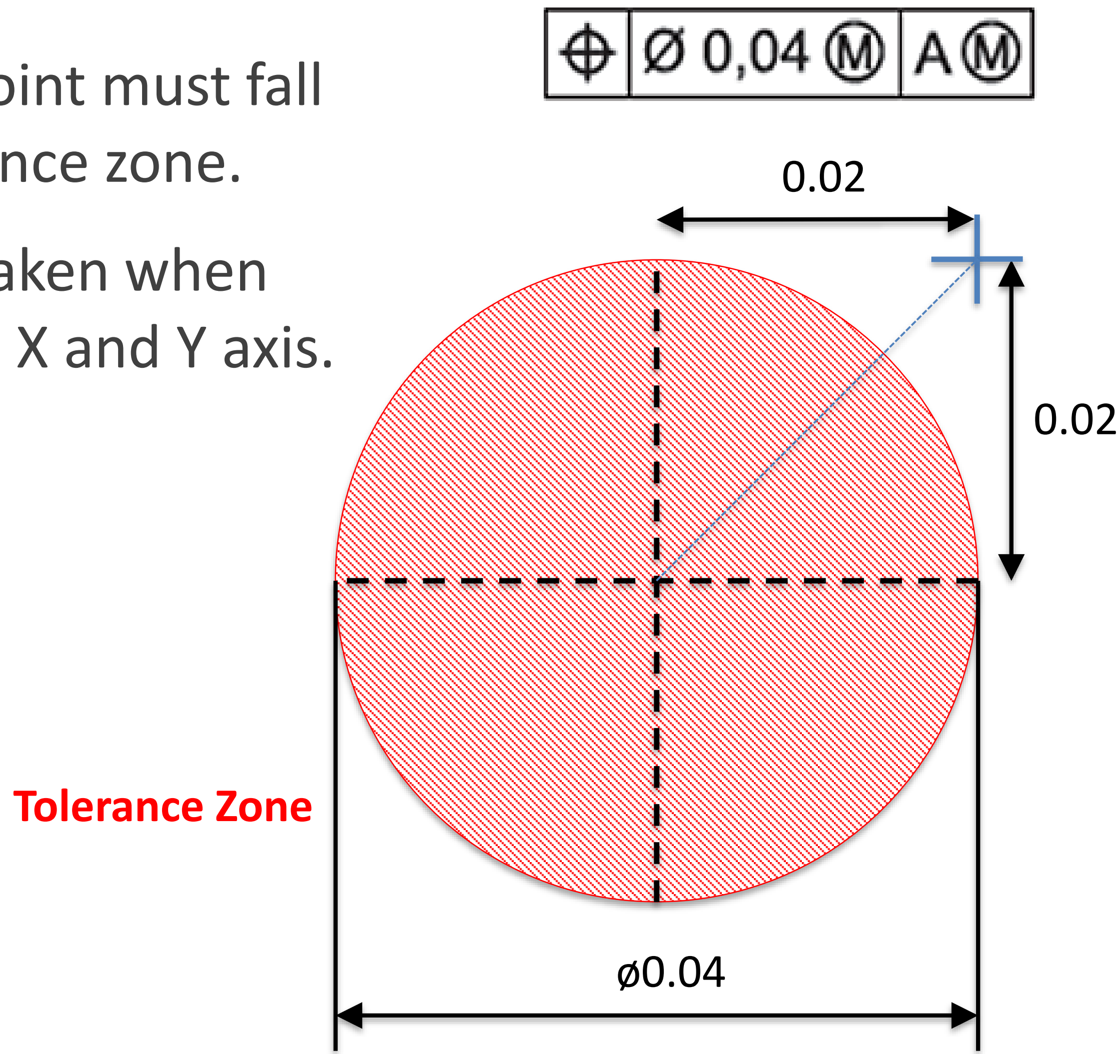
MMC applied to Datum and Feature



MMC is also applied to positional tolerance in the horizontal plane. Datum B still controls the vertical.

Diametric Tolerance

- The measured point must fall within the tolerance zone.
- Care should be taken when measuring in the X and Y axis.

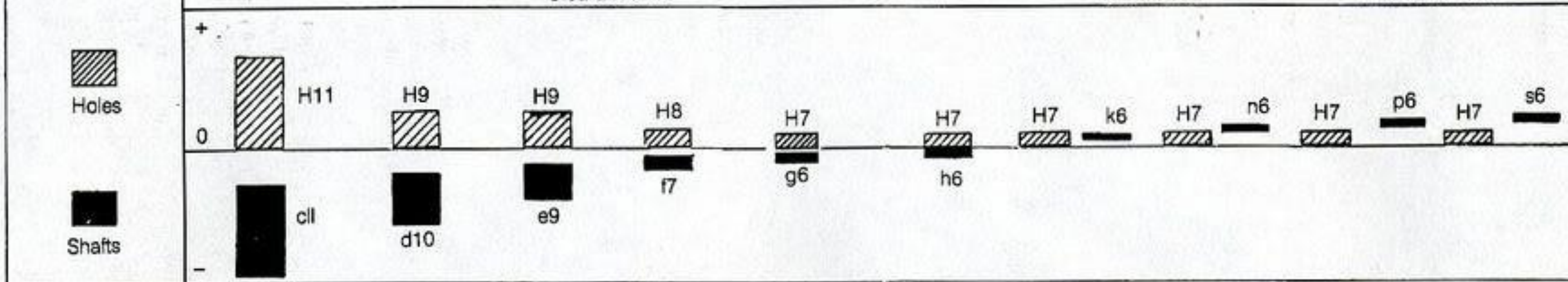


Limits and Fits

Table 1 Selected fits — hole basis

Diagram to scale for 25 mm diameter

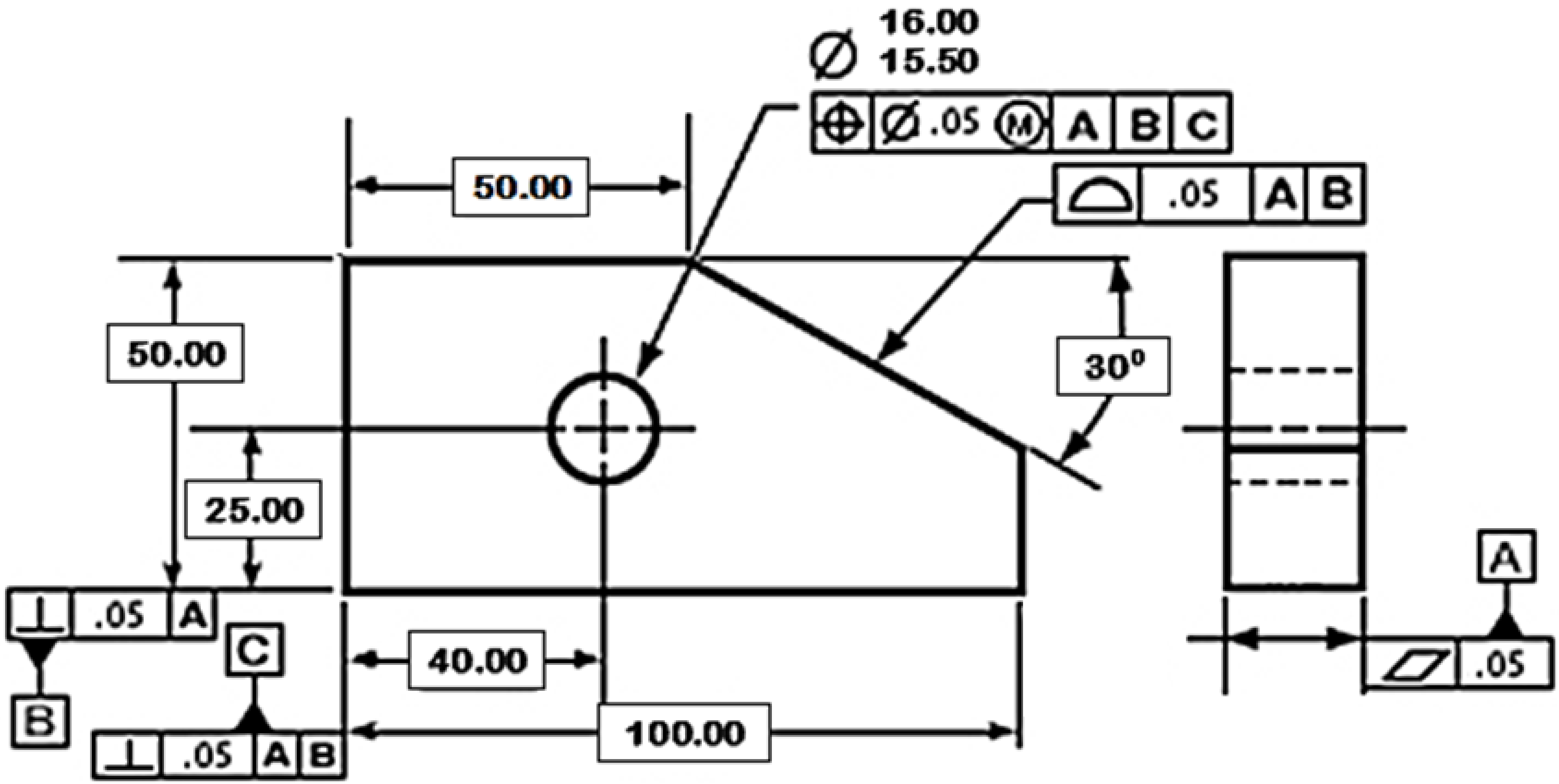
	Clearance fits	Transition fits	Interference fits



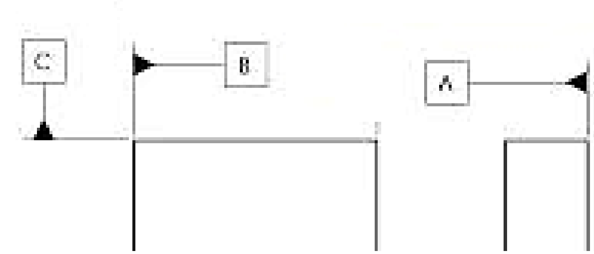
Basic size (mm)		Upper and lower deviations for tolerance class (Values μm)																			
		H11	c11	H9	d10	H9	e9	H8	f7	H7	g6	H7	h6	H7	k6	H7	n6	H7	p6	H7	s6
Above	Up to and incl.	+	–	+	–	+	–	+	–	+	–	+	–	+	+	+	+	+	+	+	+
0	3	60 0	60 120	25 0	20 60	25 0	14 39	14 0	6 16	10 0	2 8	10 0	6 0	10 0	6 0	10 0	10 4	10 0	12 6	10 0	20 14
3	6	75 0	70 145	30 0	30 78	30 0	20 50	18 0	10 22	12 0	4 12	12 0	8 0	12 0	9 1	12 0	16 8	12 0	20 12	12 0	27 19
6	10	90 0	80 170	36 0	40 98	36 0	25 61	22 0	13 28	15 0	5 14	15 0	9 0	15 0	10 1	15 0	19 10	15 0	24 15	15 0	32 23
10	18	110 0	95 205	43 0	50 120	43 0	32 75	27 0	16 34	18 0	6 17	18 0	11 0	18 0	12 1	18 0	23 12	18 0	29 18	18 0	39 28
18	30	130 0	110 240	52 0	65 149	52 0	40 92	33 0	20 41	21 0	7 20	21 0	13 0	21 0	15 2	21 0	28 15	21 0	35 22	21 0	48 35
30	40	160 0	120 280	62 0	80 180	62 0	50 112	39 0	25 50	25 0	9 25	25 0	16 0	25 0	18 2	25 0	33 17	25 0	42 26	25 0	59 43
40	50	160 0	130 290																		

BS 4500:1969

What Does this Drawing Mean?



Datum



Datum is a theoretical perfect reference feature – Primary Secondary and Tertiary.

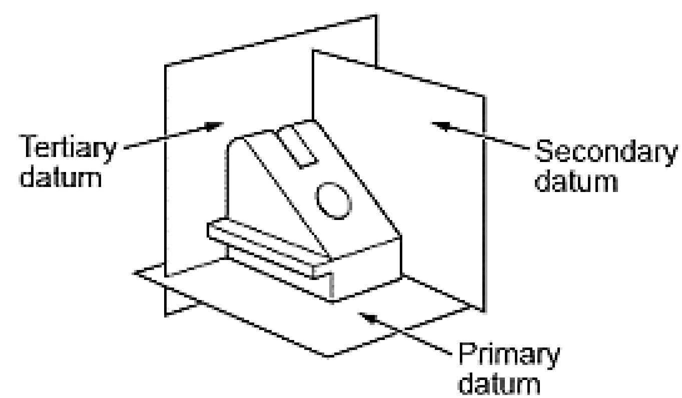
Rules for applying Datums:

Functionality of the component, datum on a functional face or feature.

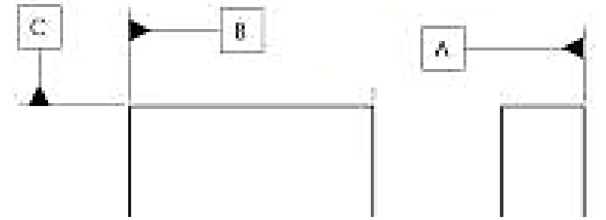
Accessibility; Datums should be easily accessed by measurement instruments.

Stability.

Repeatability.



Datum Feature



Point : Circle centre, Intersection or Point in space.

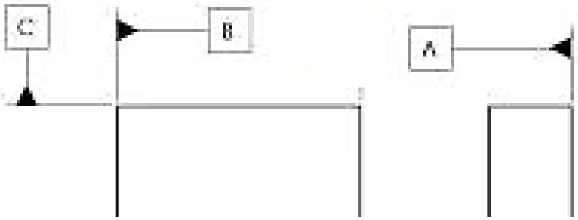
Face : Plane can be flat or cylindrical.

Line: Edges, Centre lines(axis).

Supplementary datum:

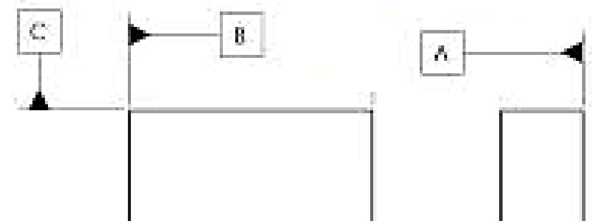
- Work holding.
- Granite face.
- V blocks.

Robust Datum

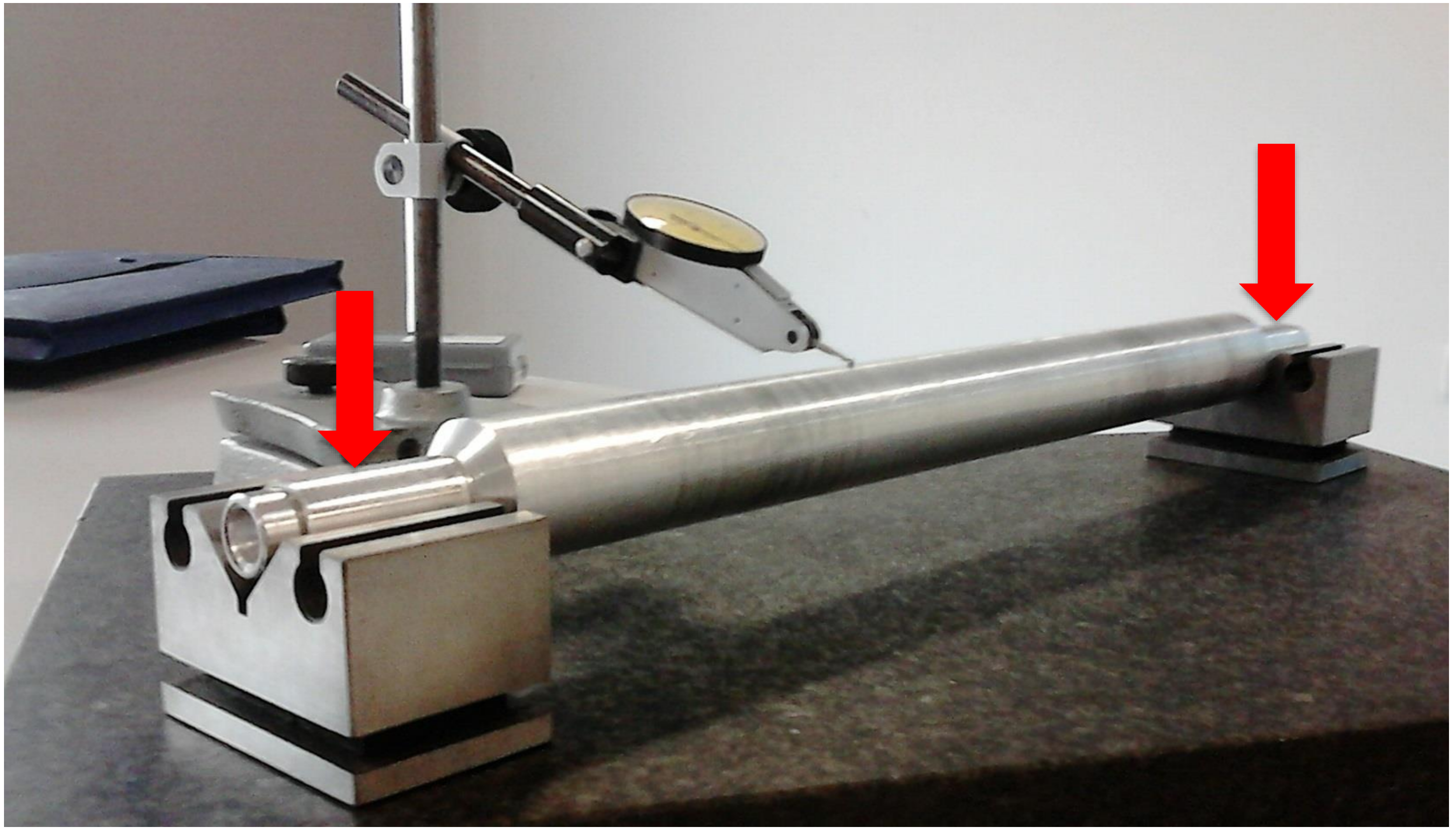


- Primary Datum should be robust and have a significant area.

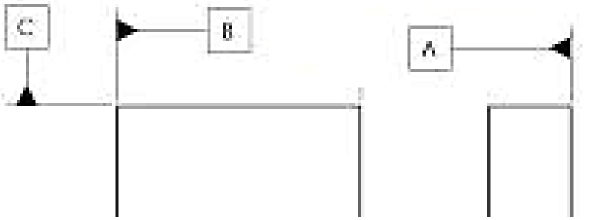
Robust Datum



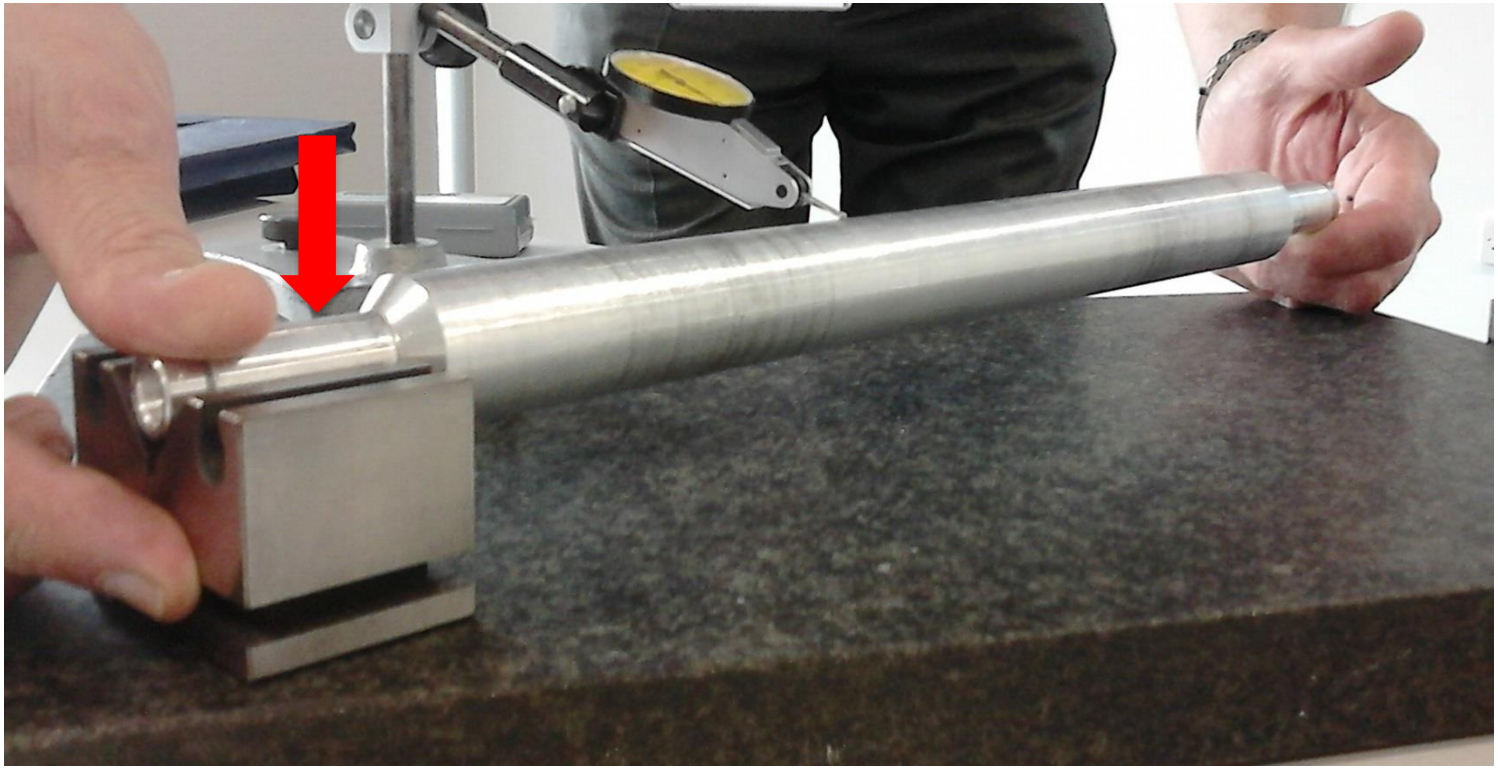
- Robust Datum constructed from two faces.



Unstable Datum



- Single face datum, difficult to fixture and prone to error.

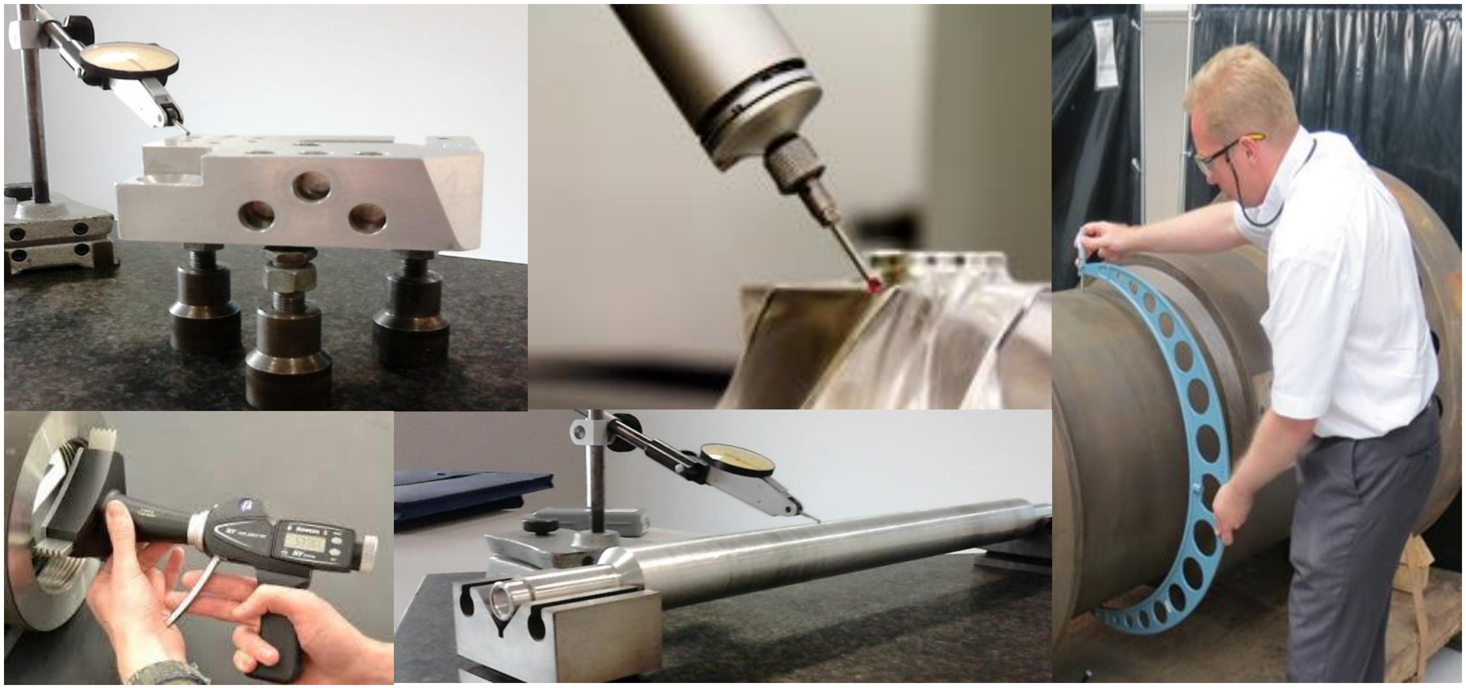


Feature

Real, geometric shapes that make up the physical characteristics of a component.

- Surfaces.
- Holes.
- Screw threads.
- Profiles.
- Faces.
- Slots.

Inspection Methods



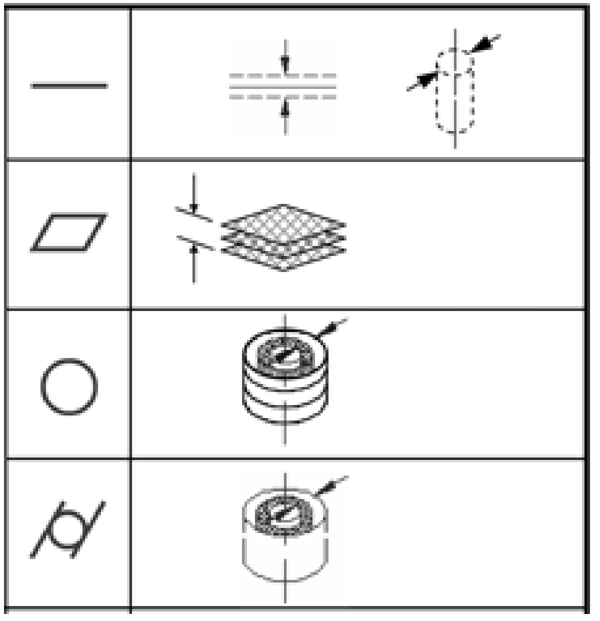
Measurement Standards

Limited standards exist that define how to inspect features:

- Surface Finish ✓
- Straightness ✗
- Flatness ✗
- Cylindricity ✗
- Roundness ✓

Form Tolerances

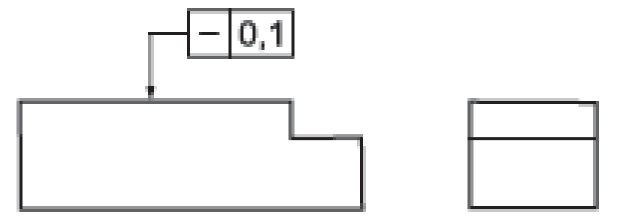
- Straightness.
- Flatness.
- Circularity (Roundness).
- Cylindricity.



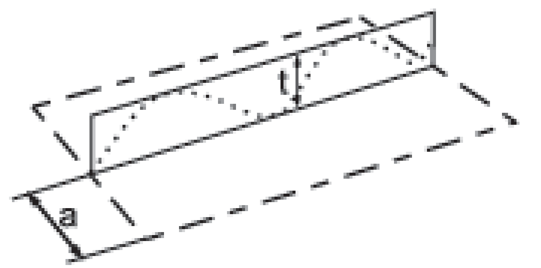
Straightness

2D Feature Datum not applied. MMC or LMC can apply to a feature of size.

Indication



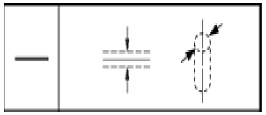
Tolerance zone



Any extracted (actual) line on the upper surface, parallel to the plane of projection in which the indication is shown, shall be contained between two parallel straight lines 0,1 apart.

Courtesy of HEXAGON METROLOGY

Straight-Edge DTI Method

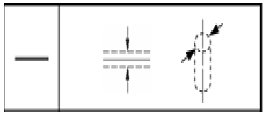


Controlling traverse

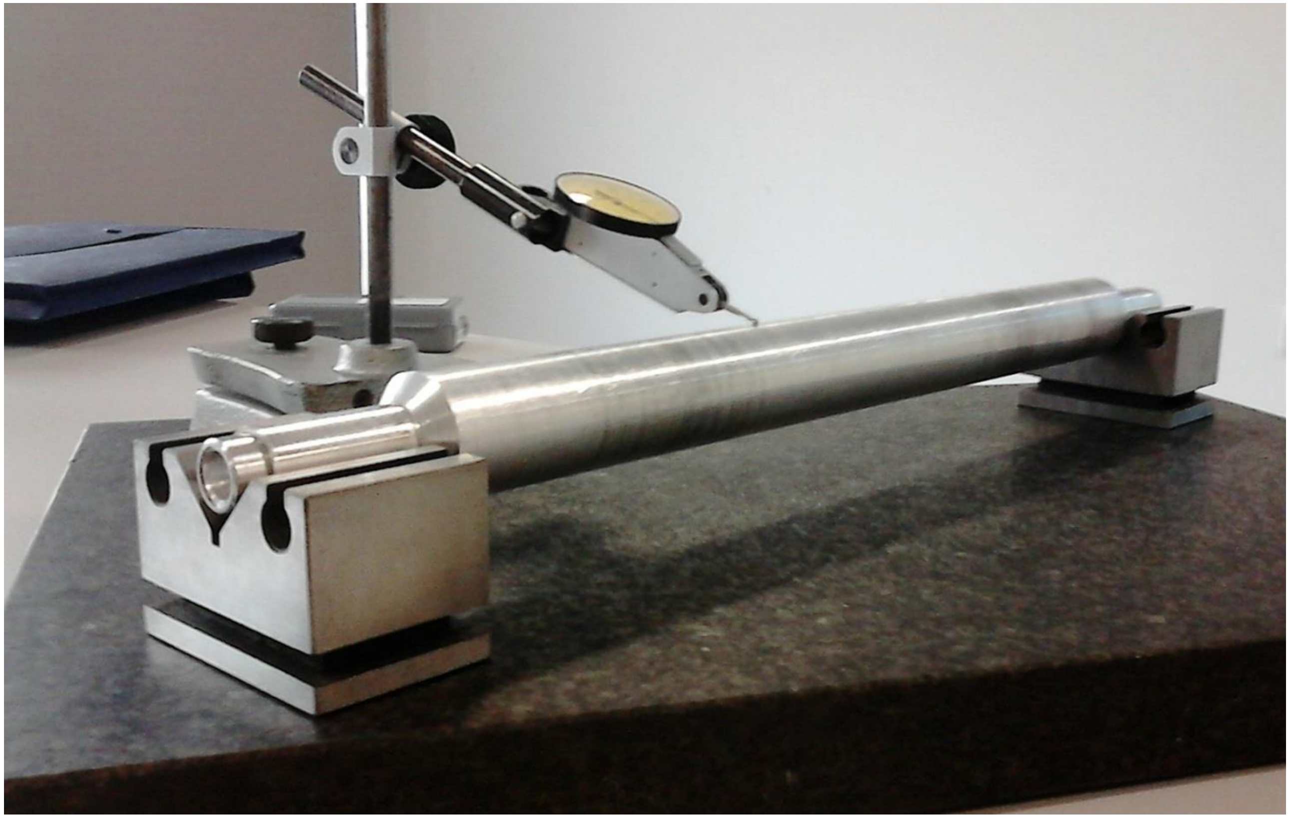
www.kunz-precision.ch

www.directindustry.com

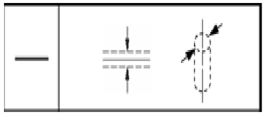
Shafts Method



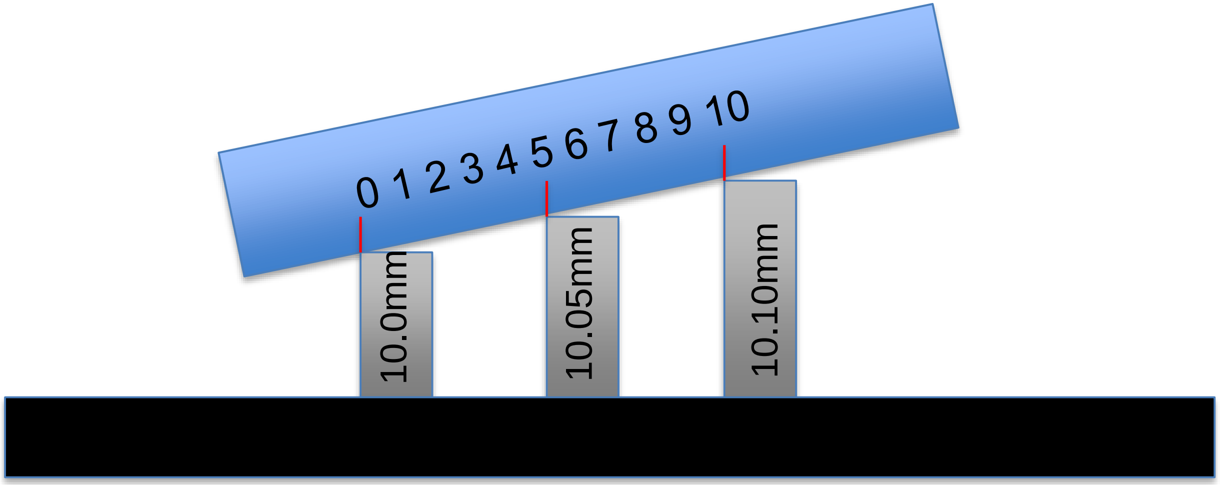
Controlling the traverse would be optimal but the measurement can be performed without this control.



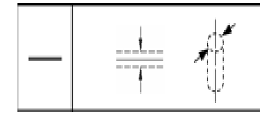
Wedge Method



- Using gauge blocks to determine the straightness.

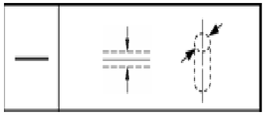


Feeler Gauge Method

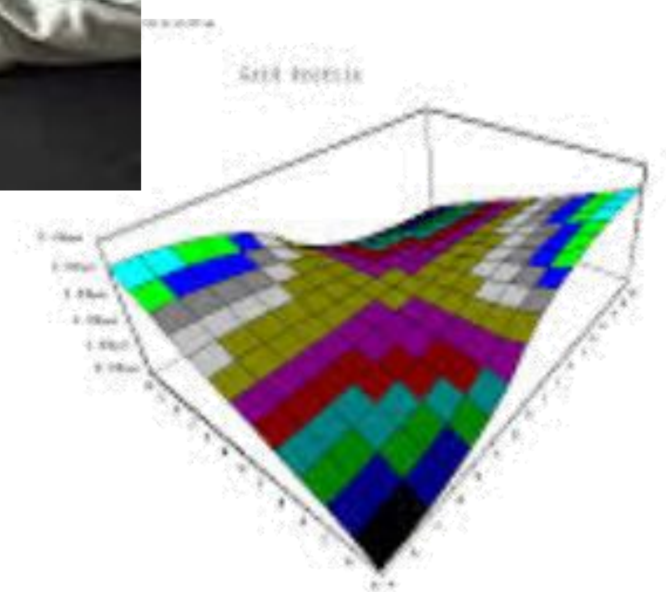


- Feeler gauges are not normally traceable.
- Blue tint to the visible light in the gap indicates 2-5 microns.

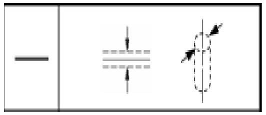
Large Scale - Level Method

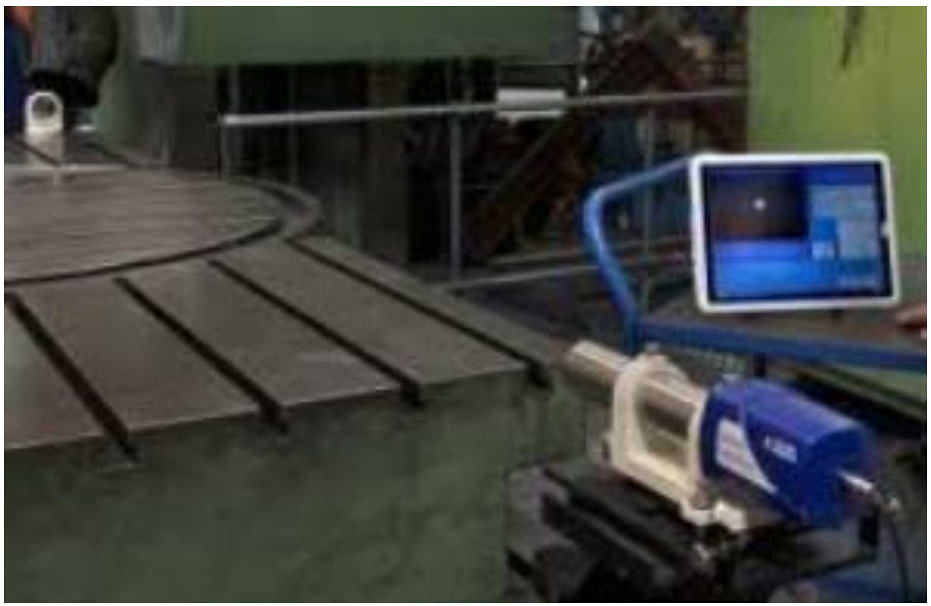


TAYLOR HOBSON®



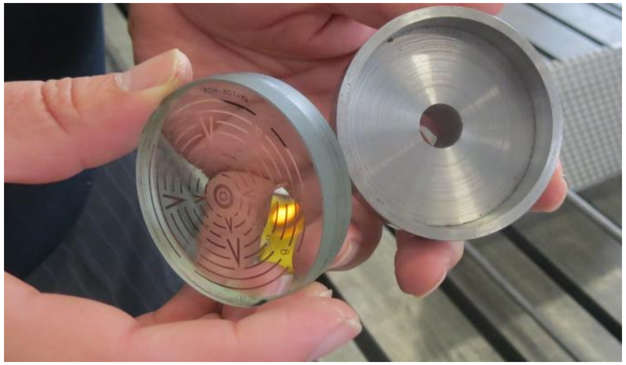
Large Scale - Autocollimator



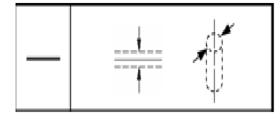


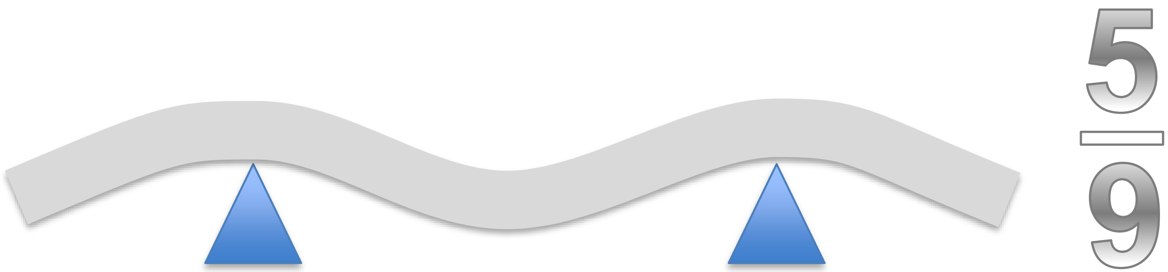
TAYLOR HOBSON®

Large Scale - Alignment Telescope



Airy and Bessel points





Airy Points = 0.5577 length

Airy points are used for two-point support, and make the end faces parallel.

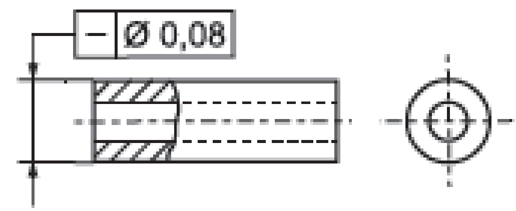
Bessel Points = 0.559 length

Bessel points are used for two-point support, and minimize the change in the overall length.

Straightness

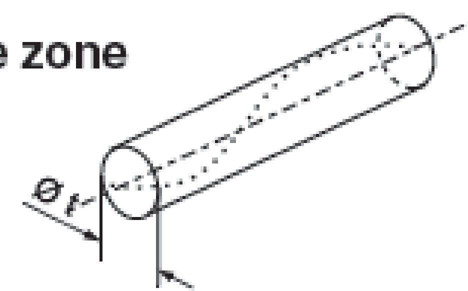
3D Feature Datum not applied.
MMC or LMC can apply to a feature of size.

Indication



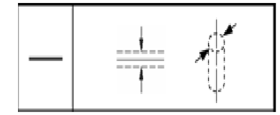
The extracted (actual) median line of the cylinder to which the tolerance applies shall be contained within a cylindrical zone of diameter 0,08.

Tolerance zone

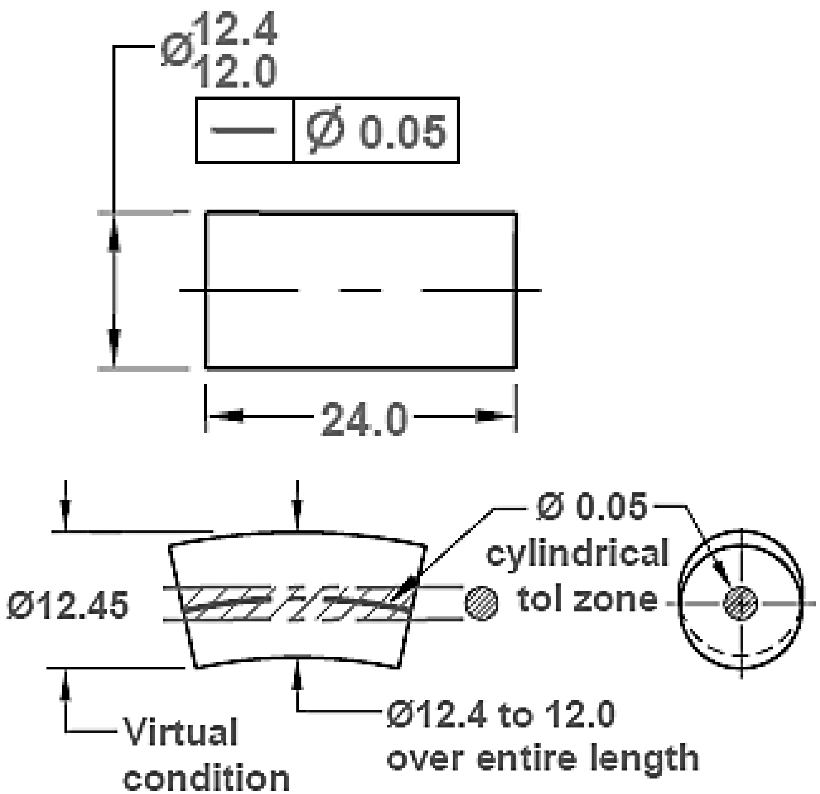


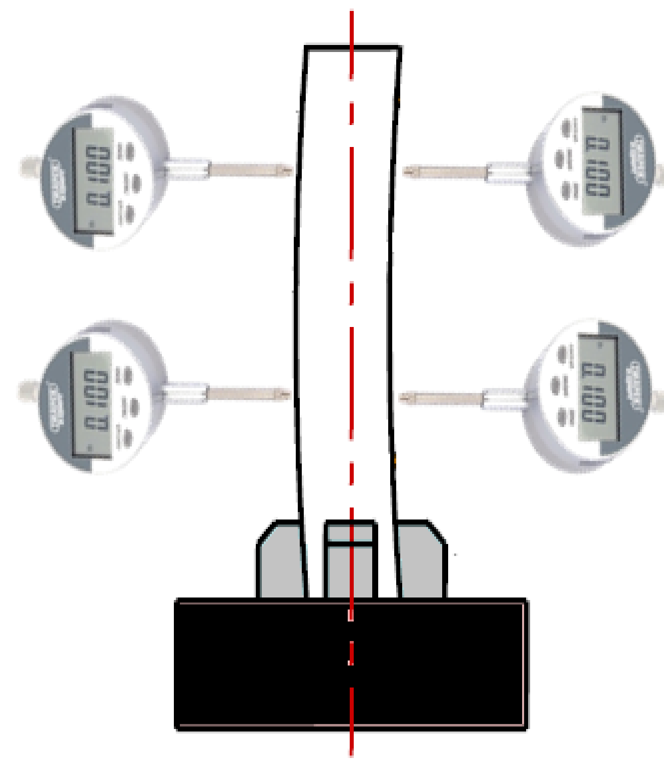
Courtesy of HEXAGON METROLOGY

Straightness Applied to Axis

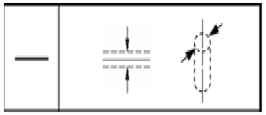


- Reference cylinder required to zero the DTI’s the difference between highest and lowest values are the total deviation. Can be deployed on a lathe.

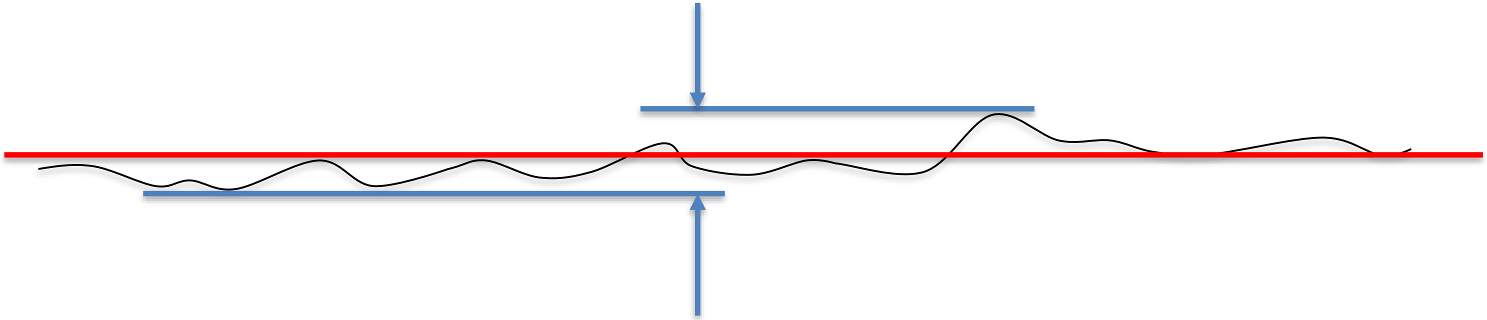




CMM



A CMM takes a best fit of all surface points and then calculates the deviation of measured points from the best fit. Alternative algorithms may result in an alternative fit.

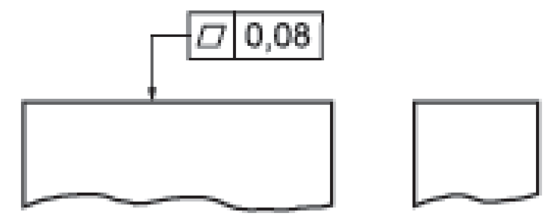


Flatness

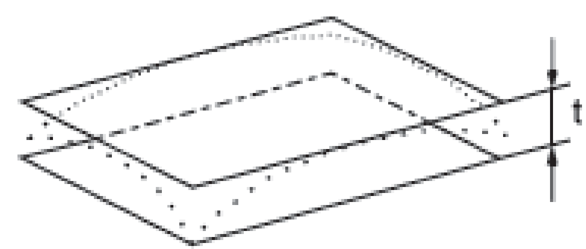
3D Feature.
Datum not applied.
MMC and LMC cannot be applied.

The extracted (actual) surface shall be contained between two parallel planes 0,08 apart.

Indication

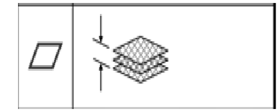


Tolerance zone

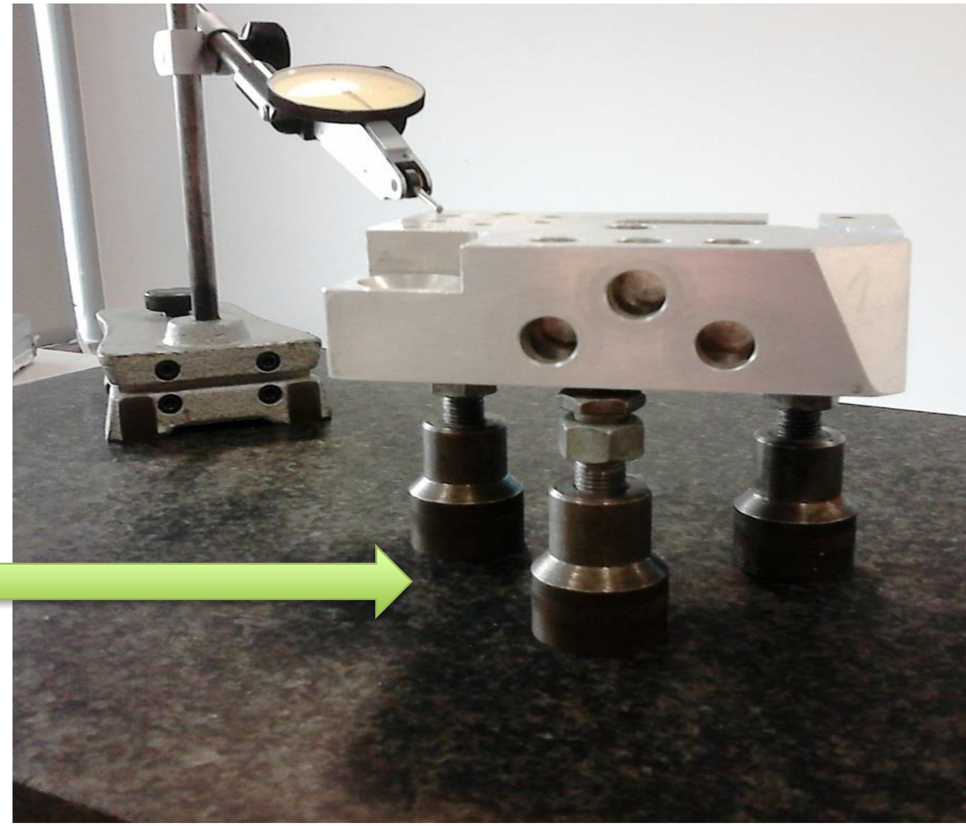


Courtesy of HEXAGON METROLOGY

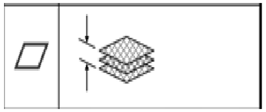
DTI Method



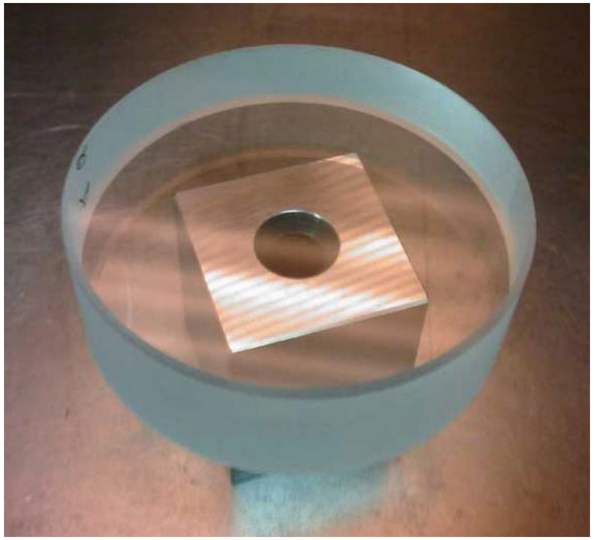
Three Jacks should be used for stability. Locating component directly on the reference surface will check parallelism not flatness.



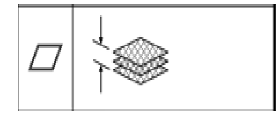
Optical Flats Method

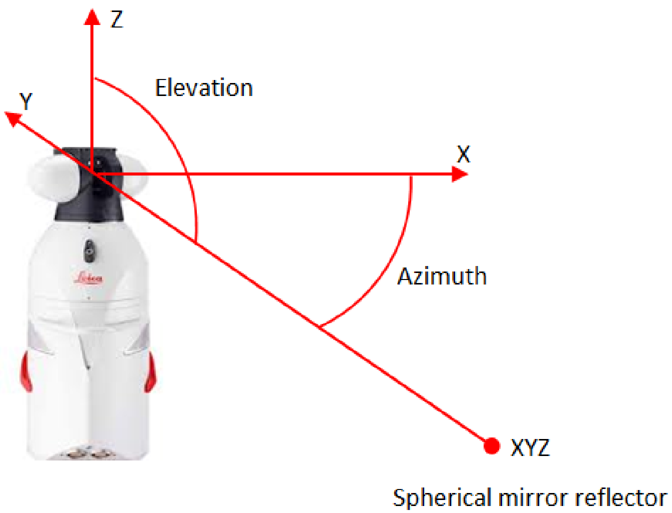


- Each fringe represent 0.3 of a micron this value is approximate because it depends on the light source.



Laser Tracker





Advantages:

Portable.

Accurate over very large distances.

Unaffected by optical properties of object.

Optional extra 6 DOF (Degrees of Freedom).

Disadvantages:

Contact process SMR target required.

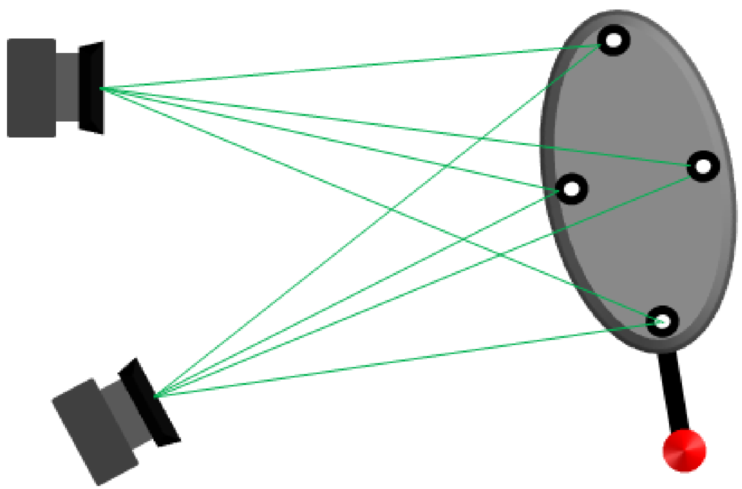
Manual process.

Relatively slow (target can be used for scanning surface).

SMR target compensation required.

Accuracy max 0.015mm + 0.006/meter.

LED Tracking



Advantages:

Portable.

6 DOF (Degrees of Freedom).

Target can be positioned to avoid line-of-sight issues.

Frequently used for robot calibration.

Disadvantages:

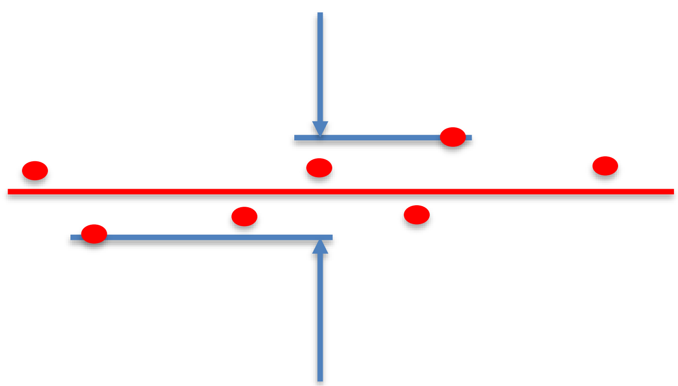
Contact process.

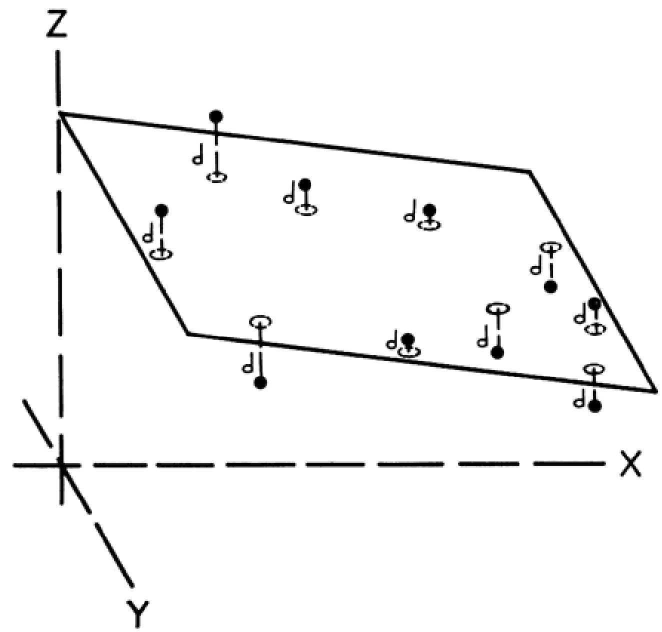
Manual process.

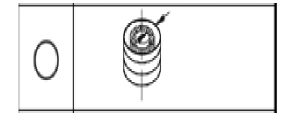
Accuracy from 50µm

CMM

A best fit plane is created to the measured points. The highest and lowest deviating measured points from this plane are used to define the flatness of the surface.





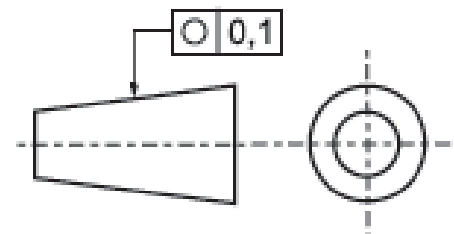


Circularity (Roundness)

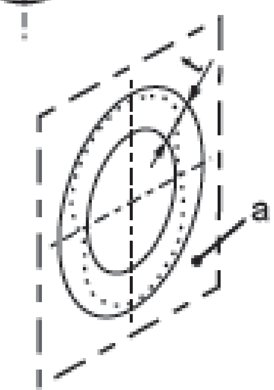
2D Feature Datum not applied.
MMC and LMC cannot be applied.

The extracted (actual) circumferential line, in any cross-section of the conical surface, shall be contained between two co-planar concentric circles with a difference in radii of 0,1.

Indication

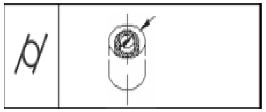


Tolerance zone



Courtesy of HEXAGON METROLOGY

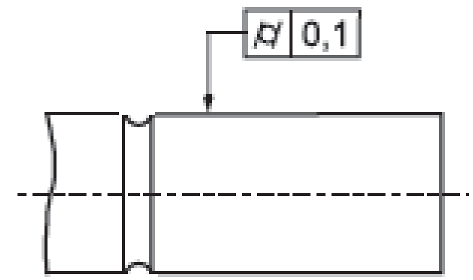
Cylindricity



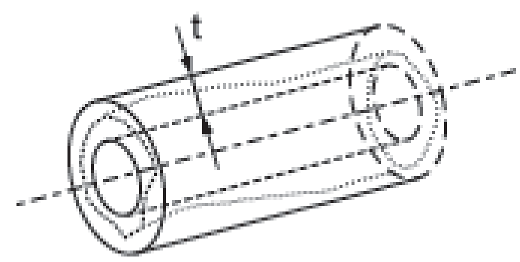
3D Feature Datum not applied.
MMC and LMC cannot be applied.

The extracted (actual) cylindrical surface shall be contained between two coaxial cylinders with a difference in radii of 0,1.

Indication

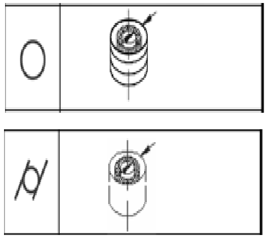


Tolerance zone

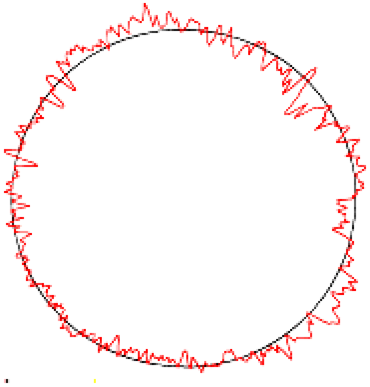


Courtesy of HEXAGON METROLOGY

Roundness Tester



- Optimal measurement instrument for the measurement of Circularity and Cylindricity.
- Limited part size and weight.



www.directindustry.com

TAYLOR HOBSON®

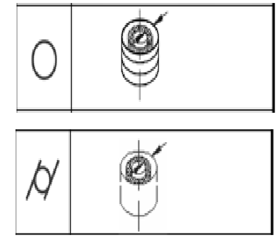
Roundness Tester

Typical Rotation Measurement Techniques

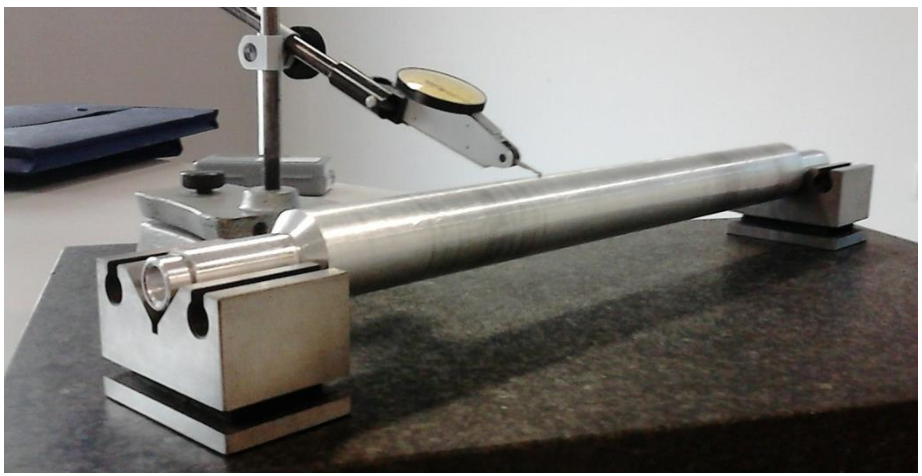
Analysis Item	Procedure	Result
Roundness (LSC/MZC/MIC/ MCC)		R max - R min
Flatness (Single-Circumference)		
Flatness (Multiple-Circumference)	1 N	
Squareness (Against Axis)		Datum axis Squareness
Squareness (Against Plane)	N	Squareness Datum plane
Concentricity		c
Coaxiality (of Section)		c
Coaxiality (of Axis)	Axis 2 Axis 1 Z	c L
Parallelism (Single-Radius)		P
Parallelism (Multiple-Radius)	1 N	P
Thickness Deviation (Radial)		d max d min d max - d min
Thickness Deviation (Axial)		d max d min d max - d min
Cylindricity	Z	MZC Cylindricity
Simplified Cylindricity	Z	Cylindricity LSC MZC MCC MIC
Mean Cylindricity	Z	Cylindricity Mean circle
Radius Variation		r1 - r2
Circular Runout (Radial)	Z	Circular runout
Circular Runout (Axial)	Z	Circular runout
Total Runout (Radial)	Z	Total runout
Total Runout (Axial)	Z N	Total runout
Diameter Measurement	Standard workpiece R Comparison	d

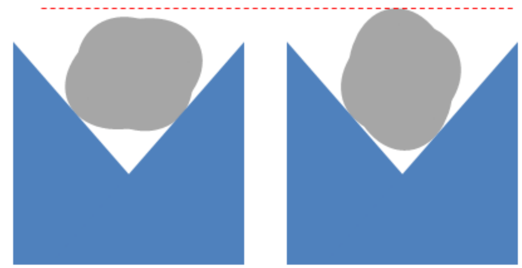
Source: Mitutoyo America Corp.

DTI and V Blocks Method



V blocks method does not provide a true value due to lobe (ovality) effects of the component surface.



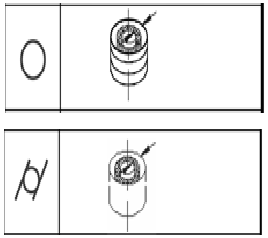


A standard, 90-degree included-angle V-block can be used to detect and count the number of lobes.

Number of Lobes	Included Angle of V-block
3	60˚
5	108˚
7	128.57˚
9	140˚

Machinery's Handbook 28th Edition

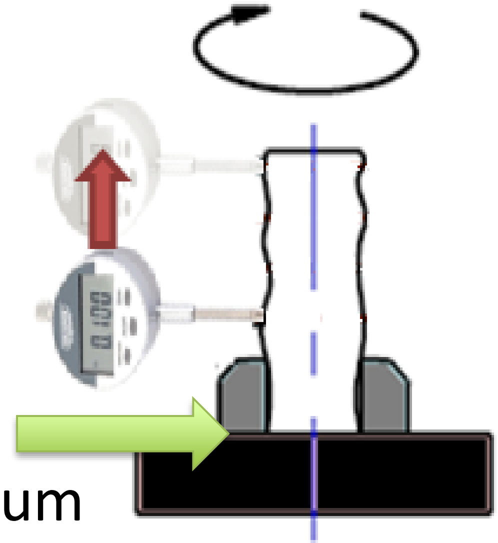
DTI and 3 Jaw Chuck Method

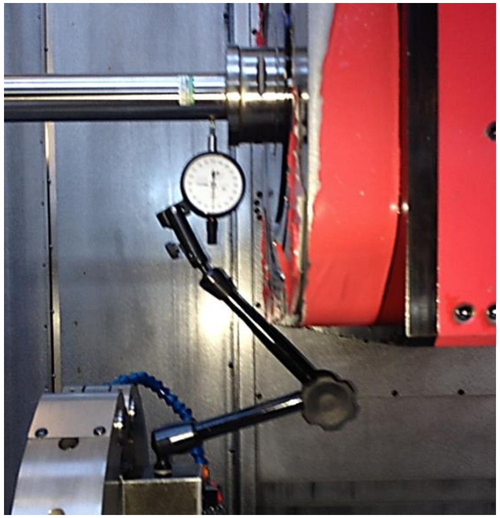


When clamping one should be aware of the lobe effect.

Often employed on the lathe during manufacture.

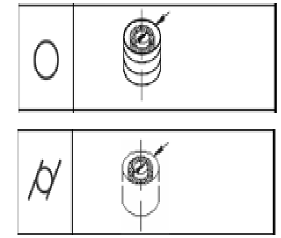
Chuck on the datum





CMM

Circularity (Roundness) and Cylindricity

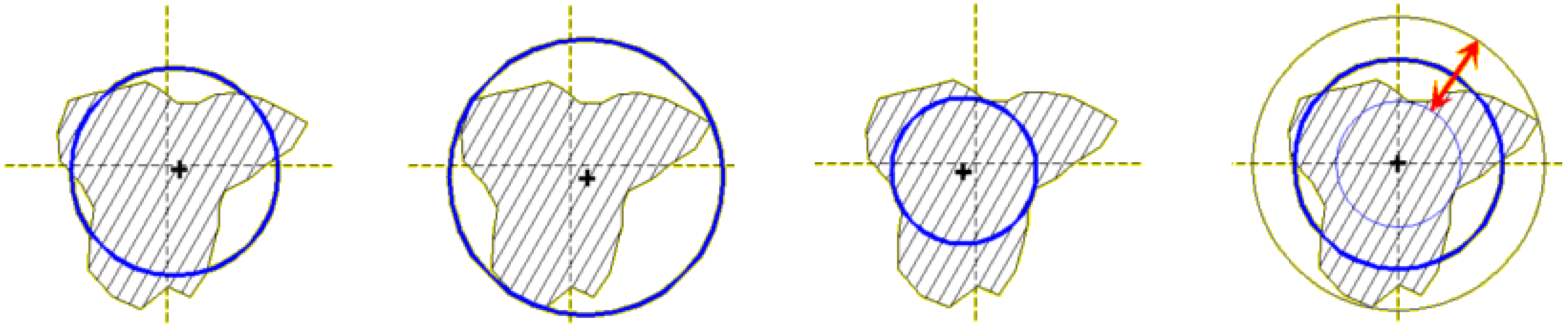


Not an optimal method for the determination of Circularity, although a scanning probe is recommend to generate sufficient point data. This point data needs to be interpreted by software algorithms to provide a measurement value.

Software filters can be applied to eliminate unwanted points generated when scanning a circle to obtain roundness, A undulations per revolution (UPR) filter will reduce the effect of surface roughness on the scanning probe, that may result in the reporting of large roundness errors.

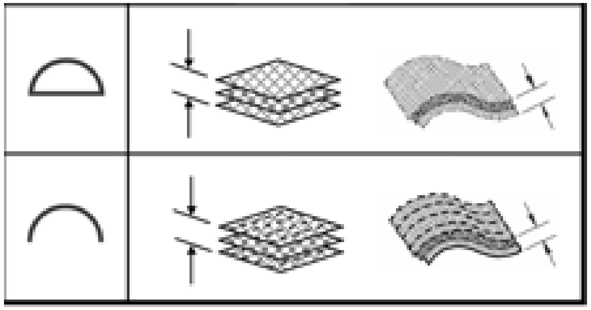
CMM Circle Fitting

- Least square circle (LSC).
- Minimum circumscribed circle (MCC).
- Maximum inscribed circle (MIC).
- Minimum zone circle (MZC).



Profile Tolerances

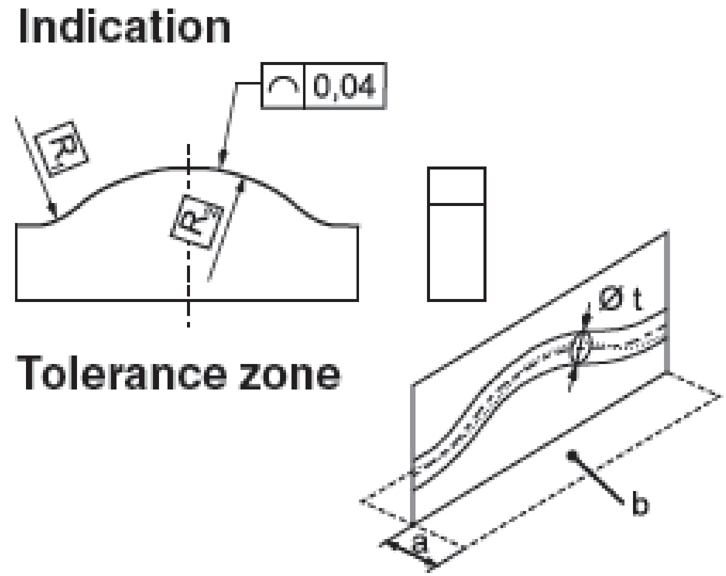
- Profile of a Surface.
- Profile of a Line.



Profile of a Line

2D Feature Datum may or may not be applied.
MMC and LMC cannot be applied.

In each section, parallel to the plane of projection in which the indication is shown, the extracted (actual) profile line shall be contained between two equidistant lines enveloping circles of diameter 0,04, the centres of which are situated on a line having the theoretically exact geometrical form.

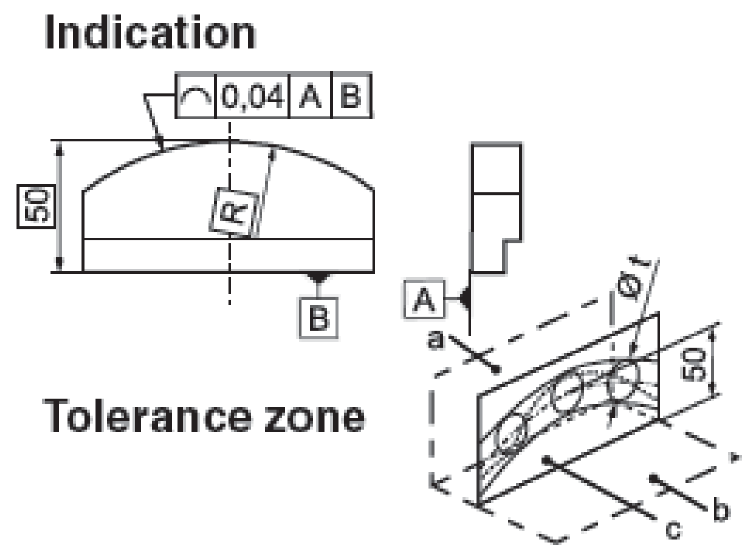


Courtesy of HEXAGON METROLOGY

Profile of a Line Related to a Datum

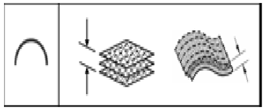
2D Feature Datum may or may not be applied.
MMC and LMC cannot be applied.

In each section, parallel to the plane of projection in which the indication is shown, the extracted (actual) profile line shall be contained between two equidistant lines enveloping circles of diameter 0,04, the centres of which are situated on a line having the theoretically exact geometrical form with respect to datum plane A and datum plane B.

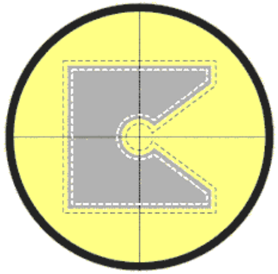


Courtesy of HEXAGON METROLOGY

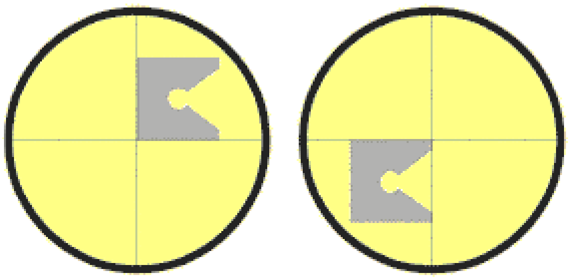
Profile Projection



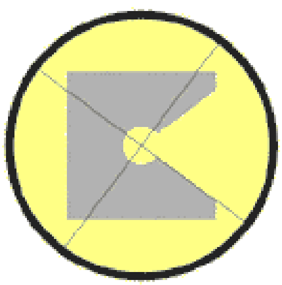
- 2D Profile and Form.



- Position.



- Angles.



10X Magnification is common.

Tool Makers Microscope

The main application of a tool maker microscope is to measure the form, size, angle, and the position of components that falls within the microscope's measuring range. Typical 30x magnification

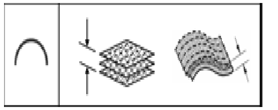
Typical Applications:

- Threads.
- Templates .
- Form and milling cutters .
- Punching tools.
- Surface finishes and surface defects.
- Hardness test indentations.

Mitutoyo 176-808A

30X Magnification is common although 100X is possible

First Principles



Simple linear forms

- DTI with the feature of interest aligned.

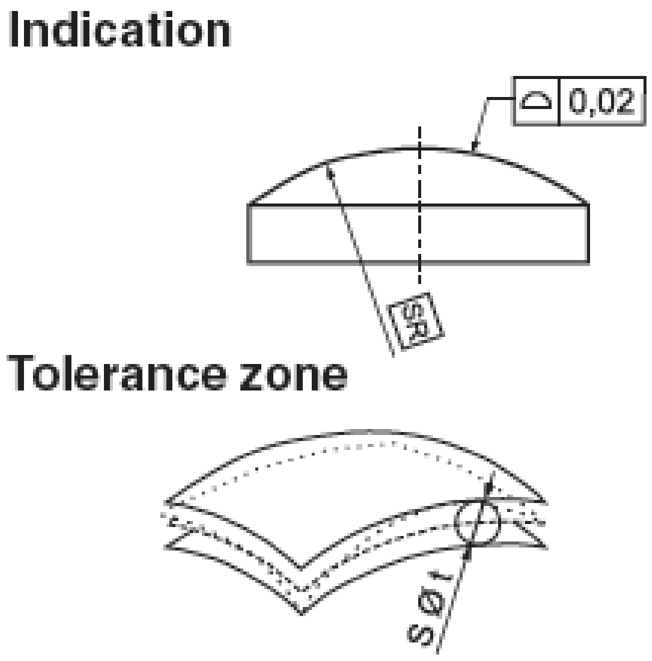
Circular forms

- 3 Jaw chuck.

Profile of a Surface

3D Feature Datum may or may not be applied.
MMC and LMC cannot be applied.

The extracted (actual) surface shall be contained between two equidistant surfaces enveloping spheres of diameter 0,02, the centres of which are situated on a surface having the theoretically
exact geometrical form.

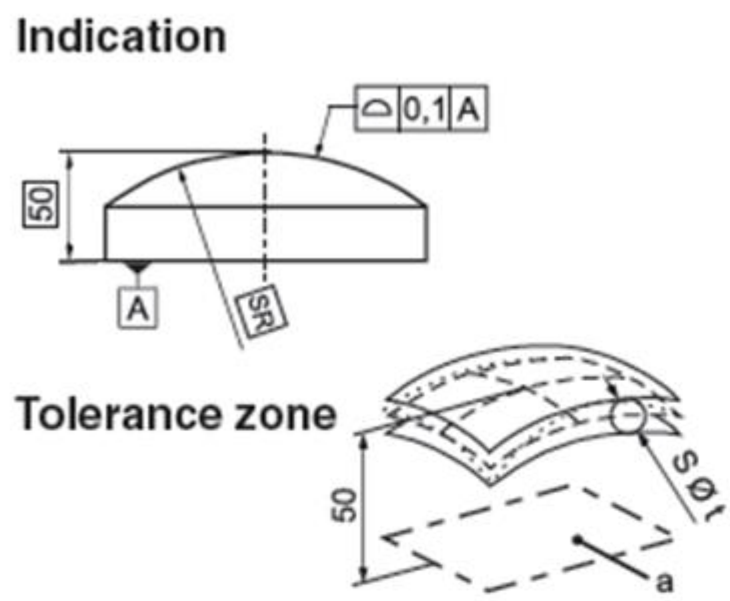


Courtesy of HEXAGON METROLOGY

Profile of a Surface Related to a Datum

3D Feature Datum may or may not be applied.
MMC and LMC cannot be applied.

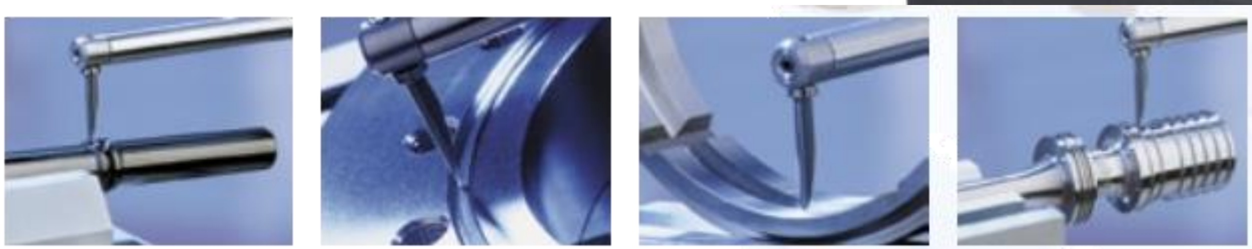
The extracted (actual) surface shall be contained between two equidistant surfaces enveloping spheres of diameter 0,1, the centres of which are situated on a surface having the theoretically exact geometrical form with respect to datum plane A.



Courtesy of HEXAGON METROLOGY

Profile Tracer

- The detection and evaluation of contours.
- Internal and external form can be measured and comparisons made between the measurements.
- Contact stylus.

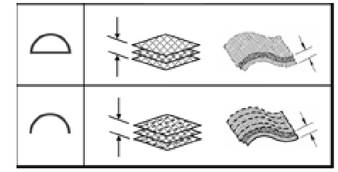


Mitutoyo Contracer Contour Measuring Instruments

3D form First Principles

Not a practical method of inspection!

Profile with CMM

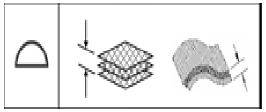


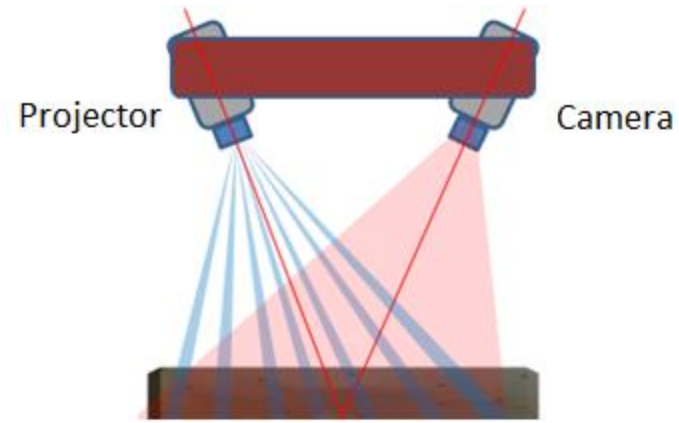
- Touch probe and scanning probes can be used to check form to complex CAD designs.
- Measured points are referenced from a common datum.

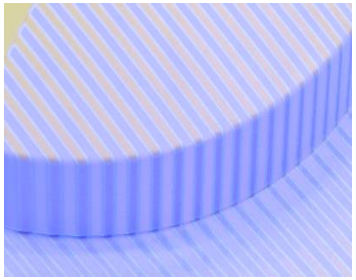
Vision Systems quick inspection of 2D profile.

Courtesy of HEXAGON METROLOGY

Structured Light







Advantages:

Non contact.

large area coverage.

Can be automated with CMM/Robot.

up to 100,000 points/sec.

High accuracy achievable.

Disadvantages:

Expensive although costs are reducing.

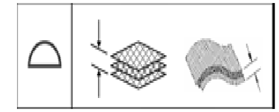
Affected ambient light conditions.

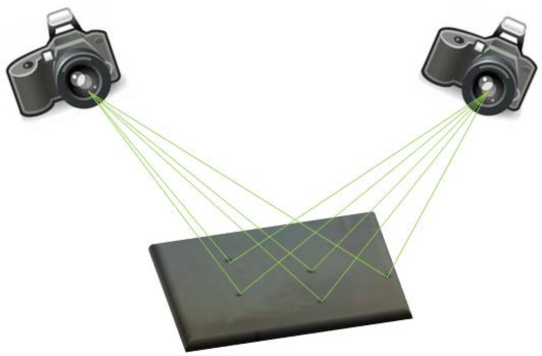
Vertical surfaces are an issue.

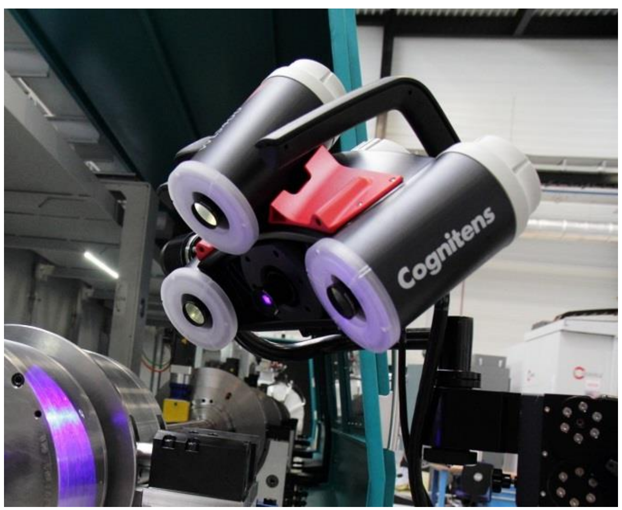
Line-of-sight limitations.

Volume	Accuracy
250mm	10µm
2m	45µm
10m	205µm

Photogrammetry







Advantages:

Non contact.

Relatively large area covered by each scan.

up to 1000,000 points/sec.

Portable.

Can be automated with a Robot.

Disadvantages:

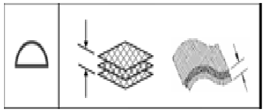
Targets required for image alignment.

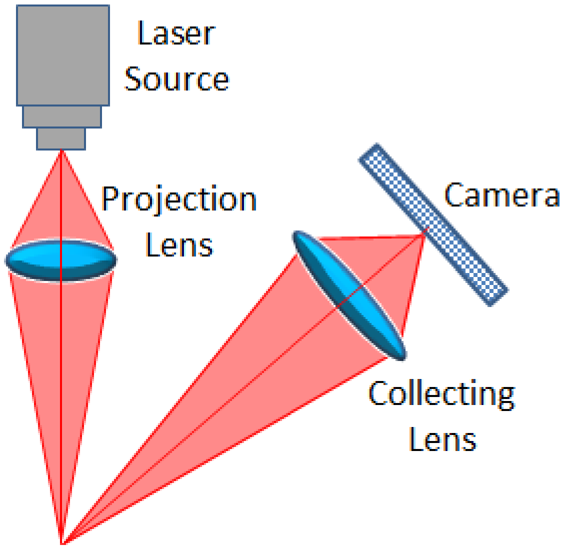
Line-of-sight limitations.

Accuracy deterioration with depth of object.

Volume	Accuracy
250mm	50µm
2m	100µm
10m	200µm

Laser Strip





Advantages:

Non contact

No probe diameter to consider

Can be fitted to CMM/Robot

15,000 points/set

Disadvantages:

Affected by optical properties of the object

Affected by ambient light

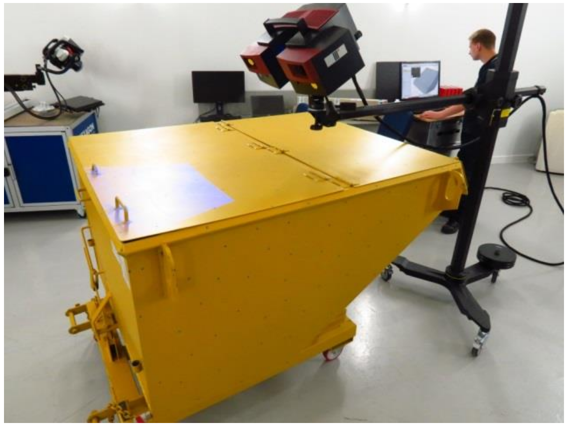
Not good on near vertical surfaces

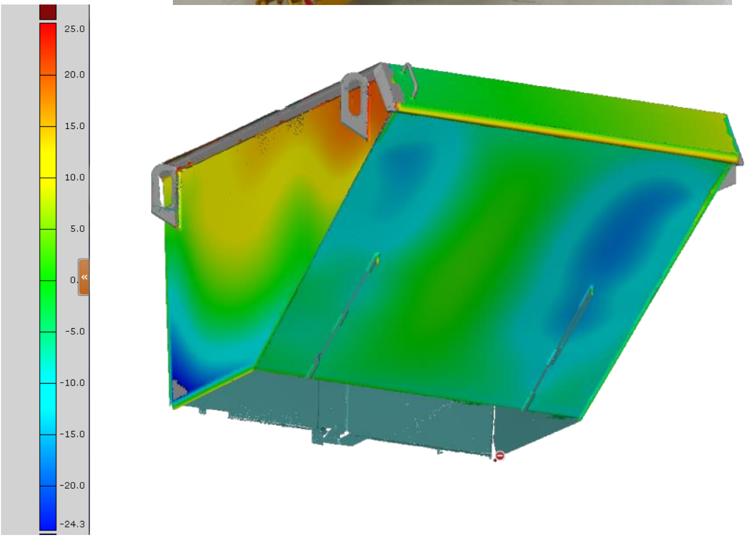
Line-of-sight limitations

Accuracy from 20µm

Images courtesy of Hexagon

Optical Metrology for Component Validation

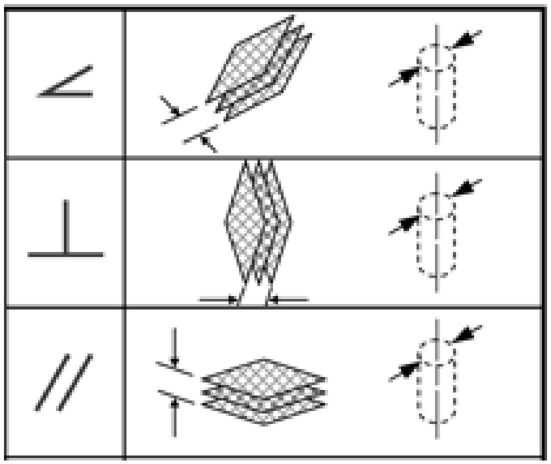




- Full form validation compared to nominal CAD.
- Primitive geometry can be fitted; cylinder and planes allow tolerance such as Cylindricity, Angularity, Flatness etc. to be inspected.
- Traceability is an issue.

Orientation Tolerances

- Angularity.
- Perpendicularity.
- Parallelism.

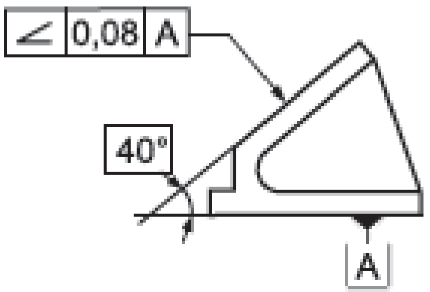


Angularity

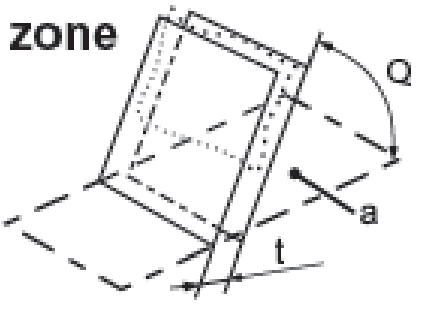
At least one datum must be referenced.
MMC or LMC can apply to a feature of size.

The extracted (actual) surface shall be contained between two parallel planes 0,08 apart that are inclined at a theoretically exact angle of 40° to datum plane A.

Indication



Tolerance zone



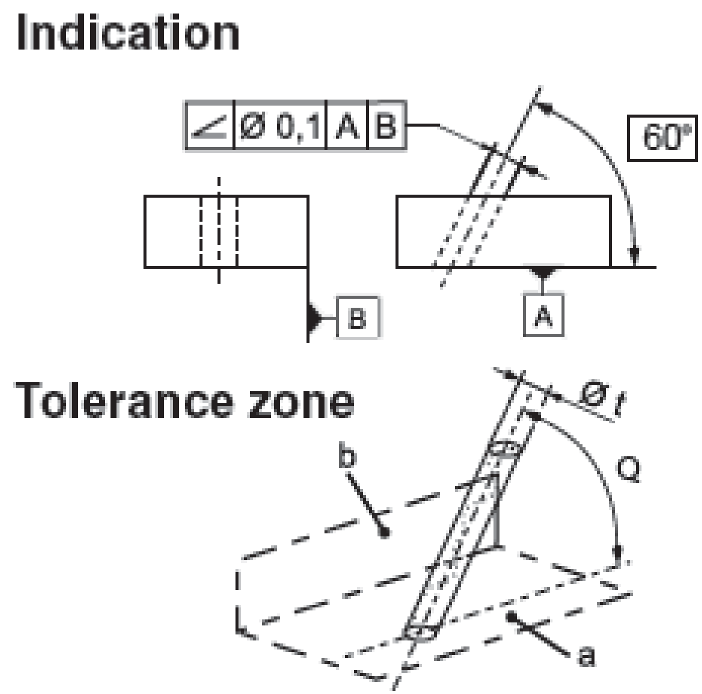
Courtesy of HEXAGON METROLOGY

Angularity

At least one datum must be referenced

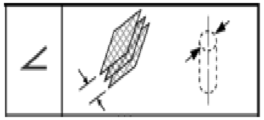
MMC or LMC can apply to a feature of size.

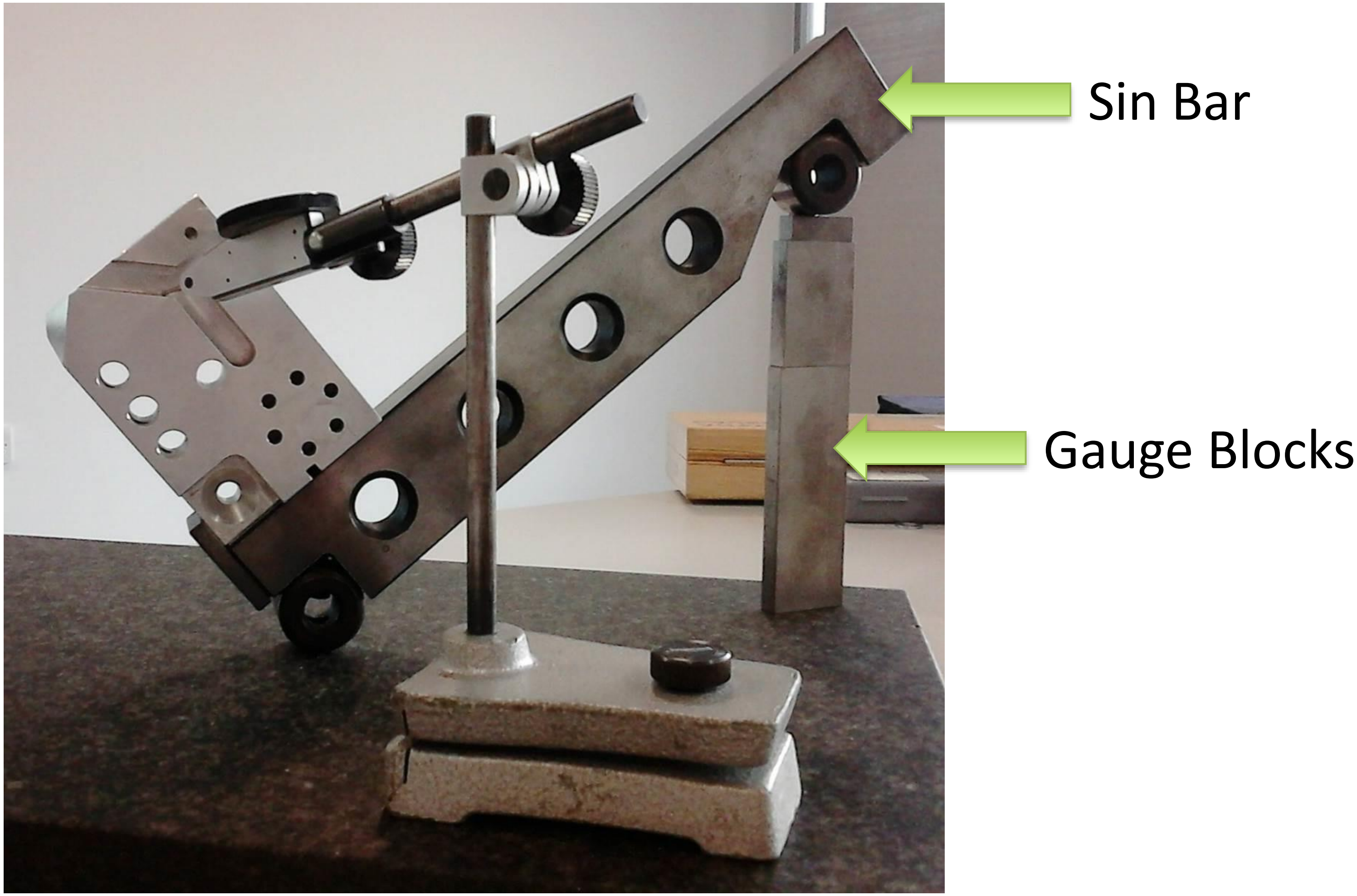
The extracted (actual) median line shall be within a cylindrical tolerance zone of diameter 0,1 that is parallel to datum plane B and inclined at a theoretically exact angle of 60° to datum plane A.



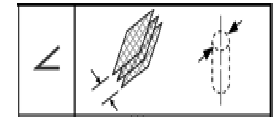
Courtesy of HEXAGON METROLOGY

Sin Bar Method





Sin Bar Method



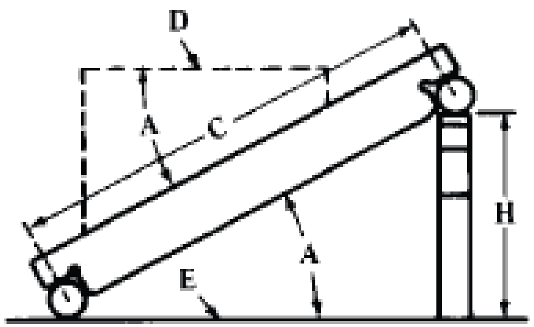


Fig. 1.

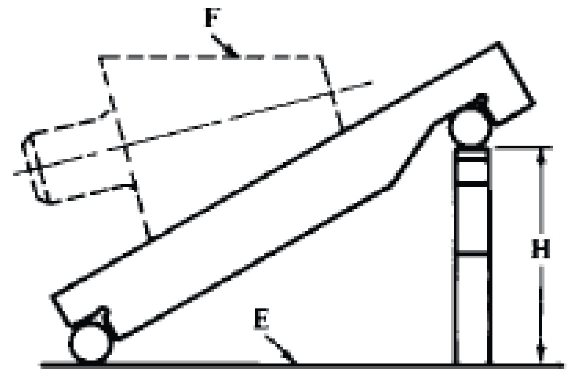


Fig. 2.

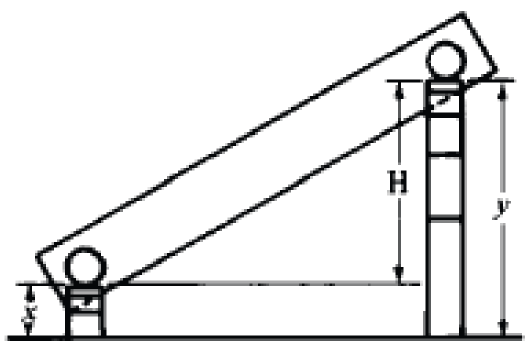


Fig. 3.

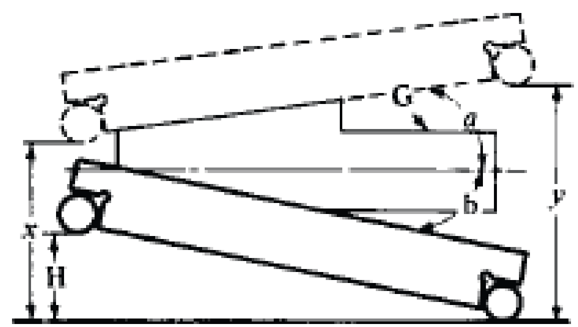


Fig. 4.

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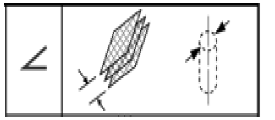
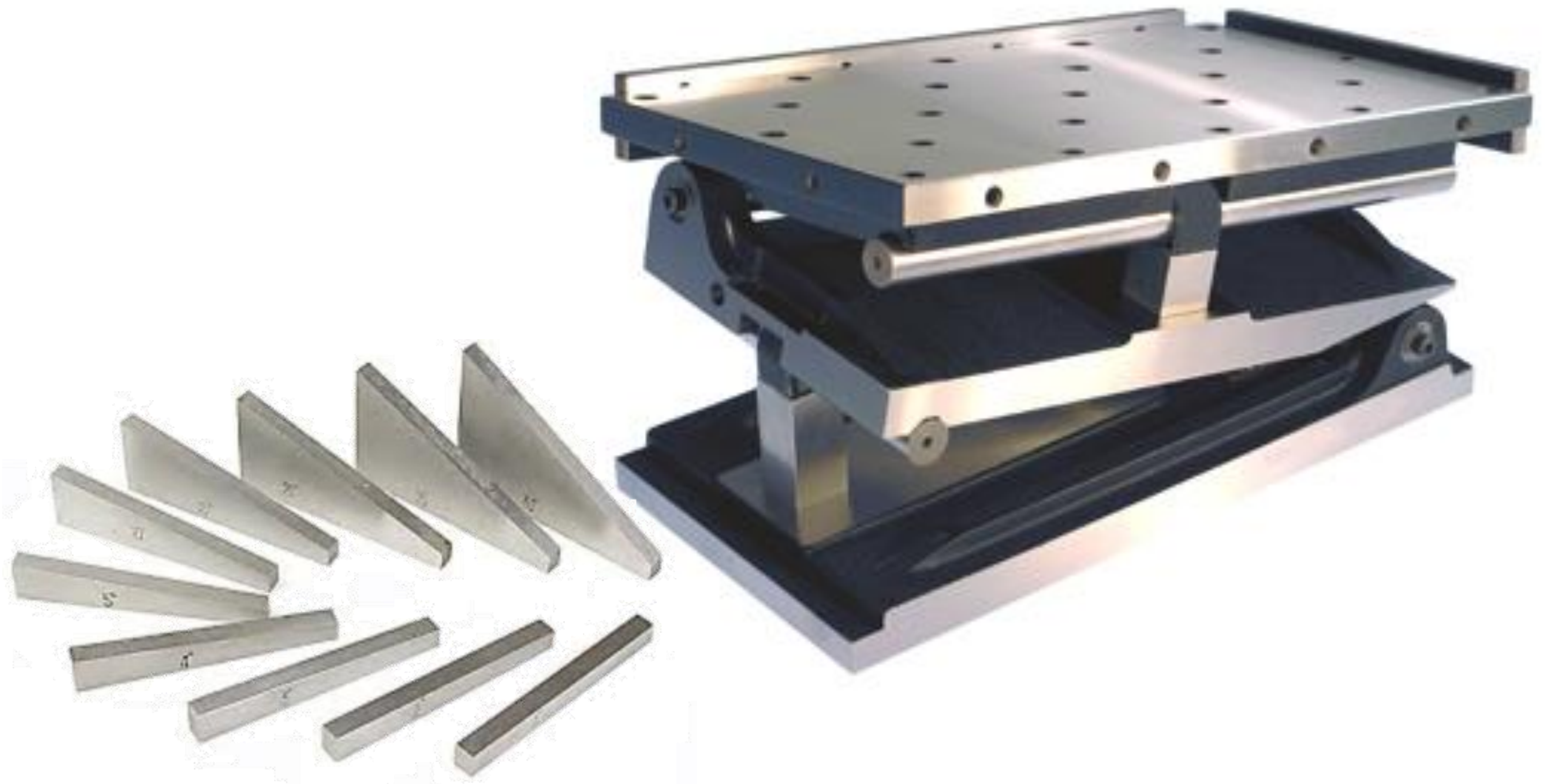
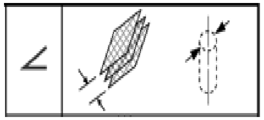
Angle Gauge Blocks & Sin Table



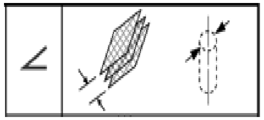


Indexing Rotary Table



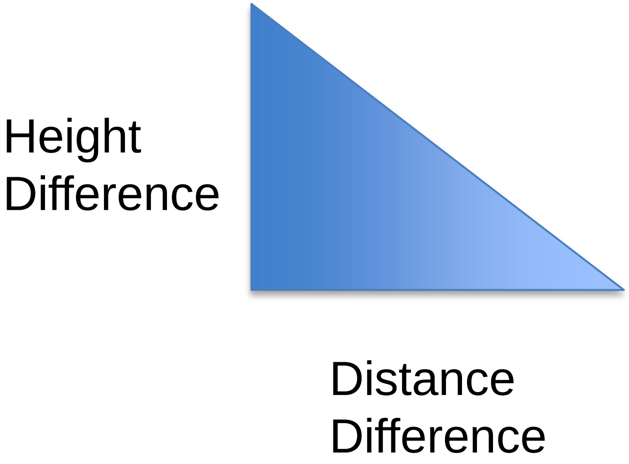
Dividing Head

Height Gauge Method

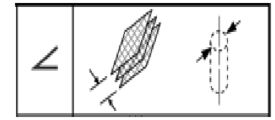


Gauge Block

Gauge Block



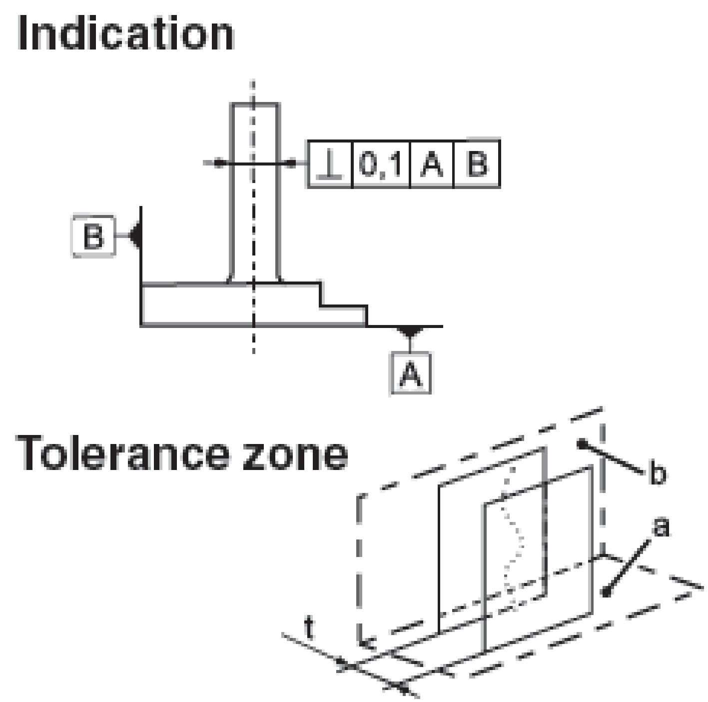
Universal Bevel Protractor



Perpendicularity

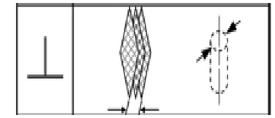
At least one datum must be referenced.
MMC or LMC can apply to a feature of size.

The extracted (actual) median line of the cylinder shall be contained between two parallel planes 0,1 apart that are perpendicular to datum plane A and in the direction specified with respect to datum plane B.

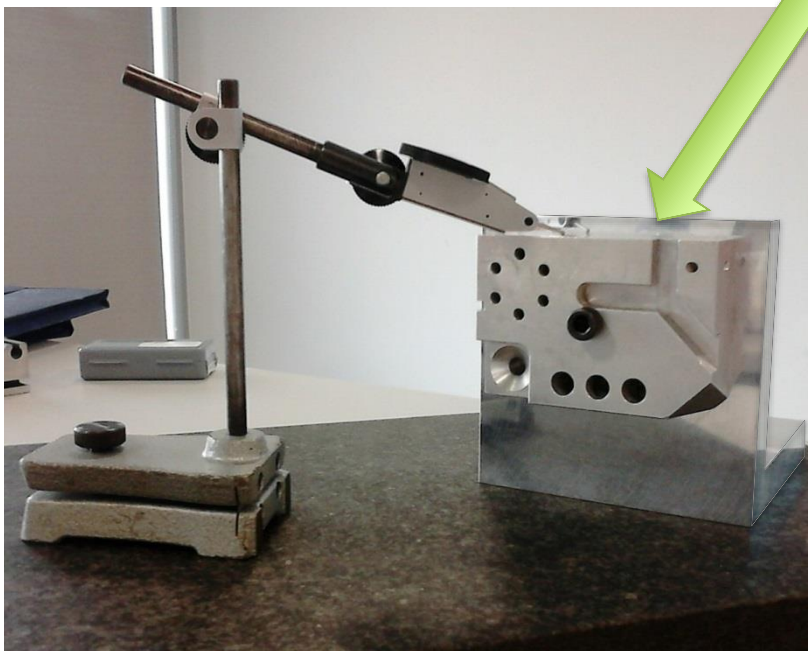


Courtesy of HEXAGON METROLOGY

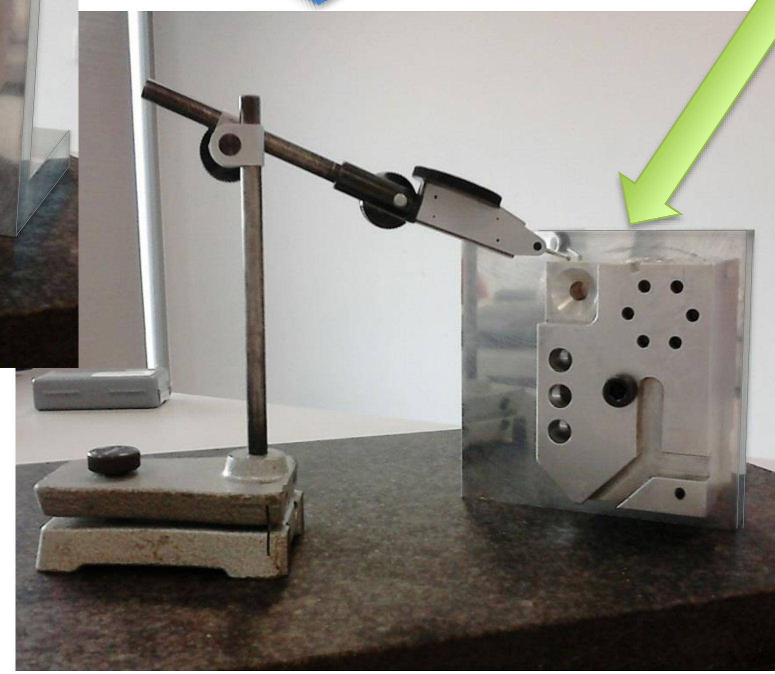
DTI Method

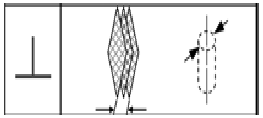


Datum Face



Measured Face

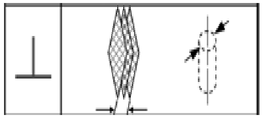




Height Gauge Method

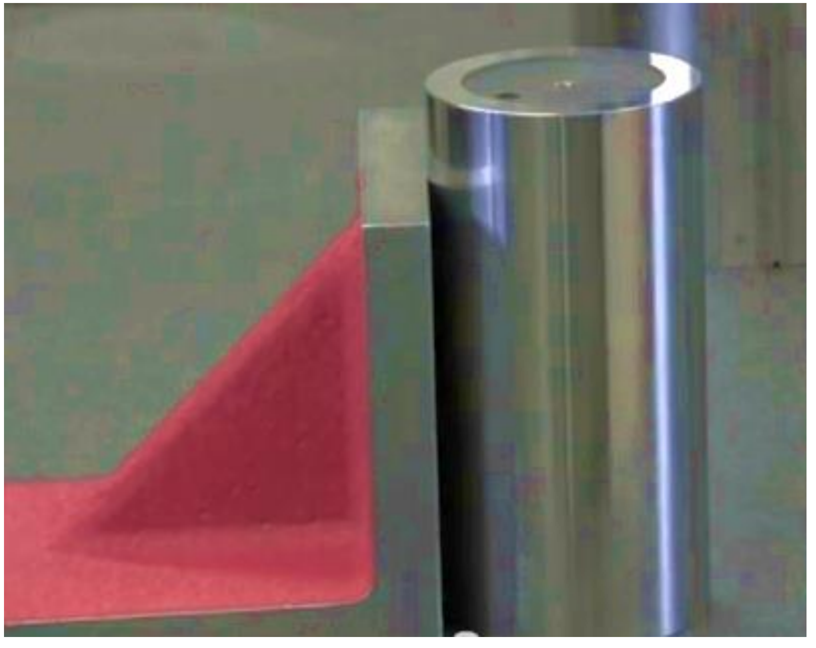
Check the cleanliness of component and reference surface interface. Remember Abbe's Principle and the effects of bending moments.

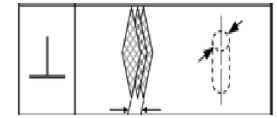
Engineer square and Feeler Gauges or Gauge Blocks.



Cylinder Square Method

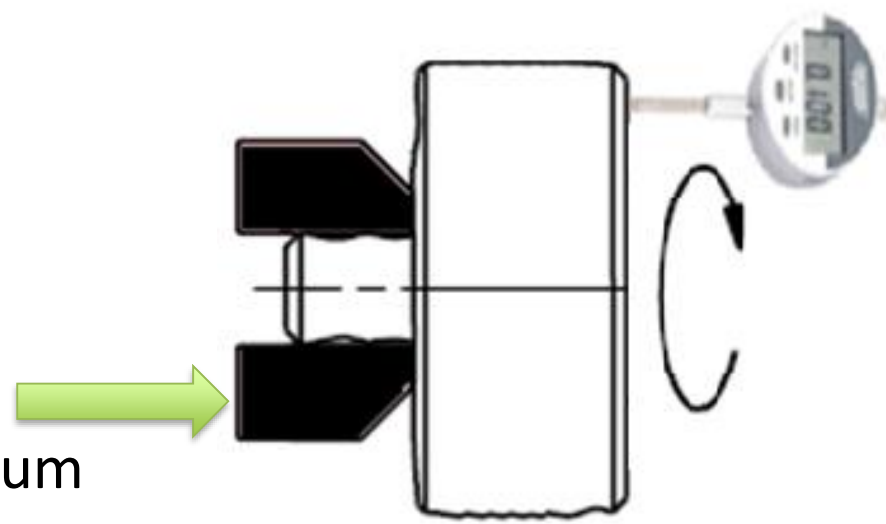
Magnetic Cylinder Square





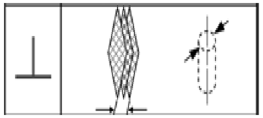
DTI Method

- Fixture on the datum face and check the Perpendicularity of the rotating face with DTI .

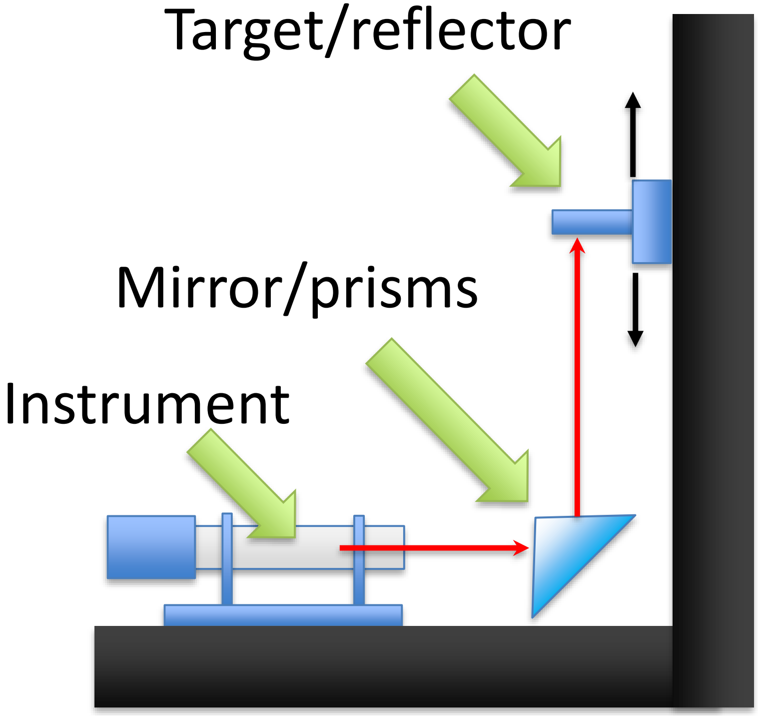


Chuck on the datum

Large Scale



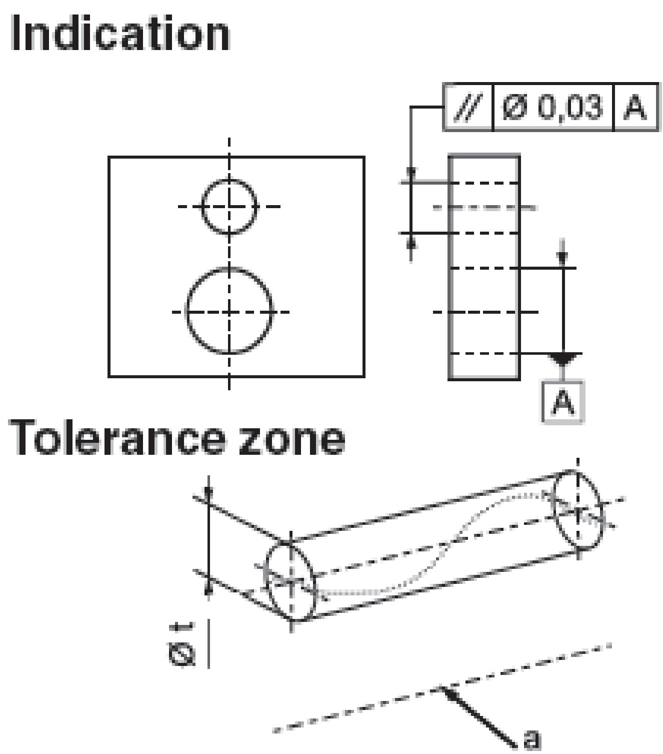
- Autocollimator and Alignment Telescope.



Parallelism

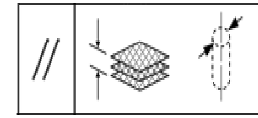
At least one datum must be referenced.
MMC or LMC can apply to a feature of size.

The extracted (actual) median line shall be within a cylindrical zone of diameter 0,03 parallel to the datum axis A.

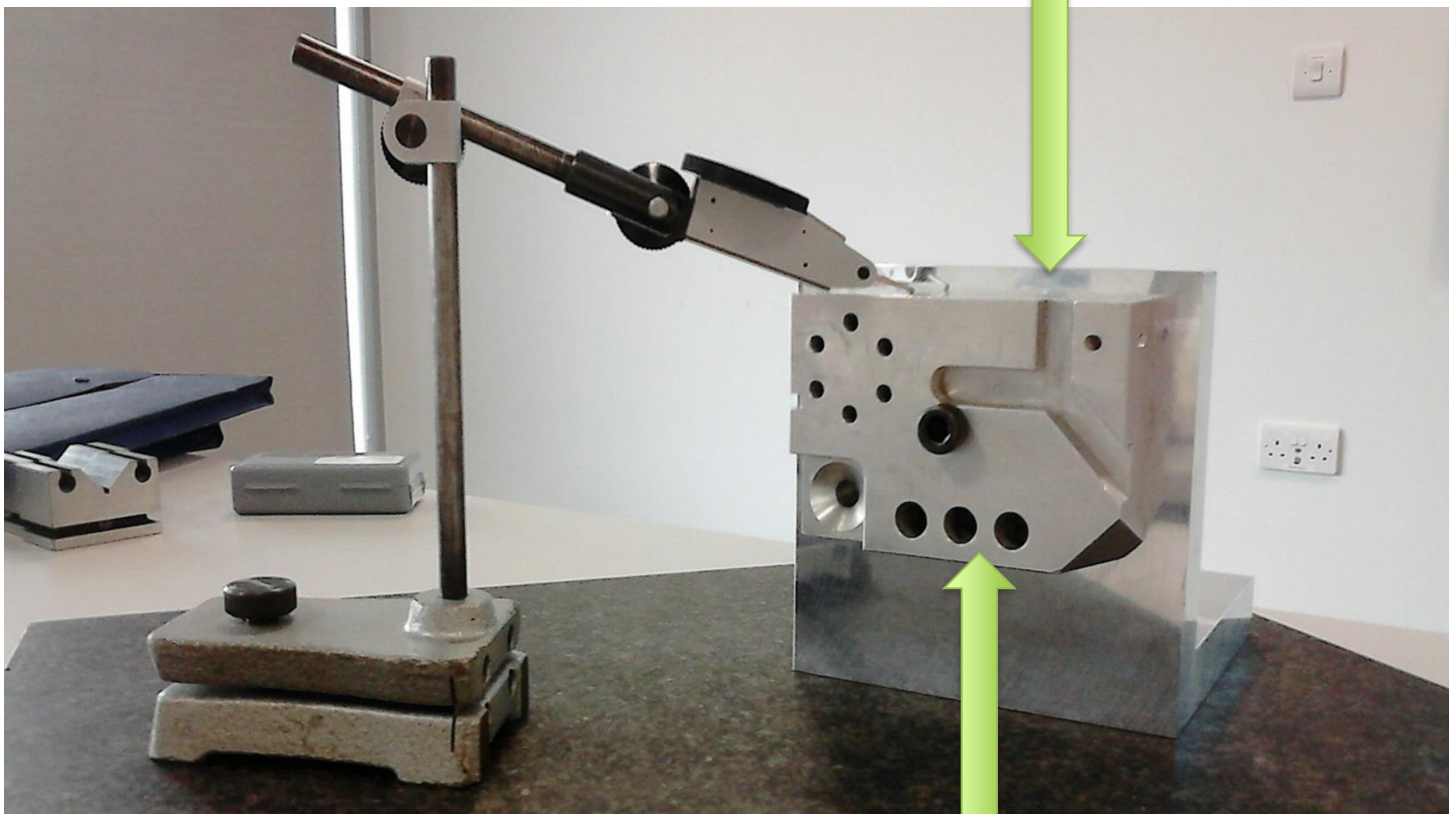


Courtesy of HEXAGON METROLOGY

DTI Method

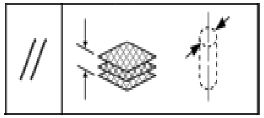


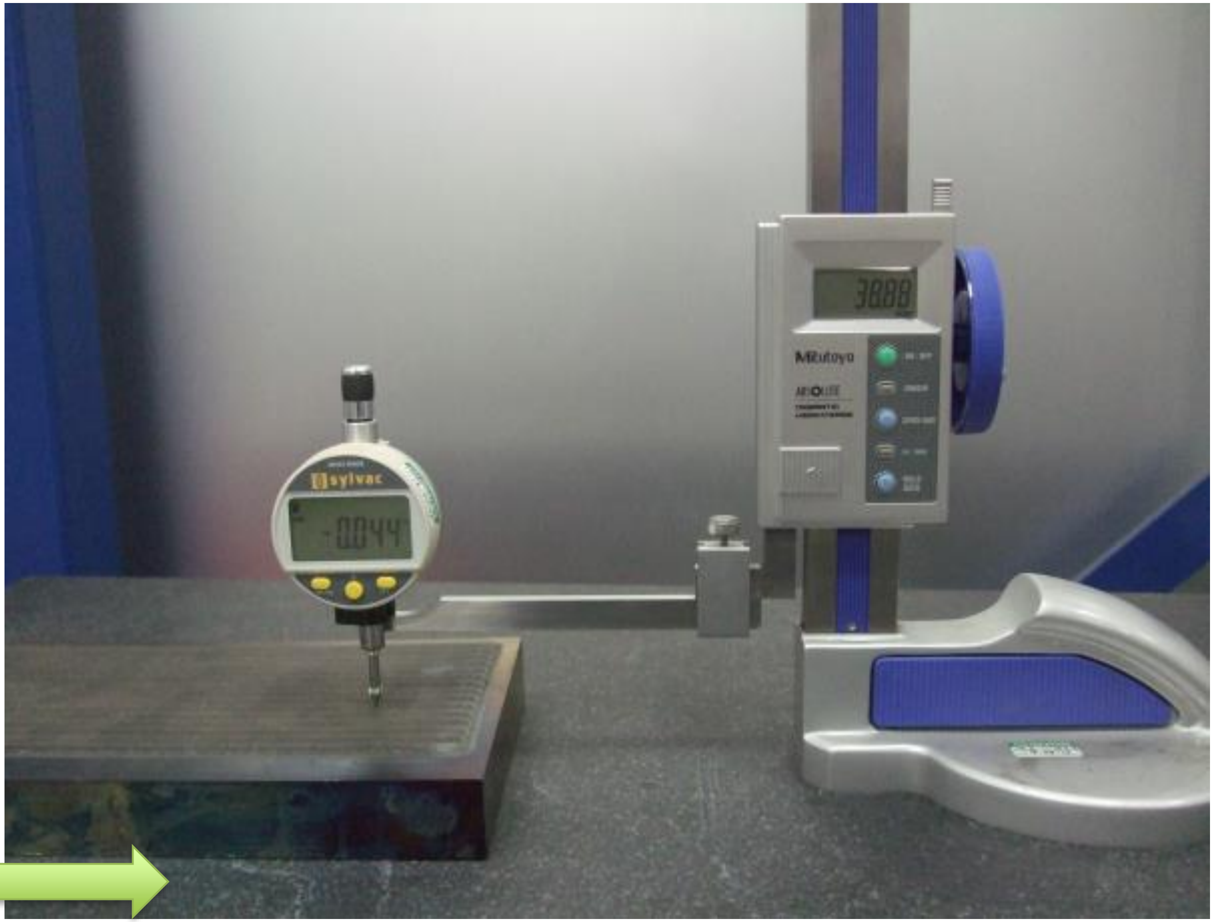
Measured Face



Zero the datum face

Height Gauge Method

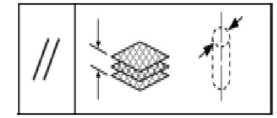




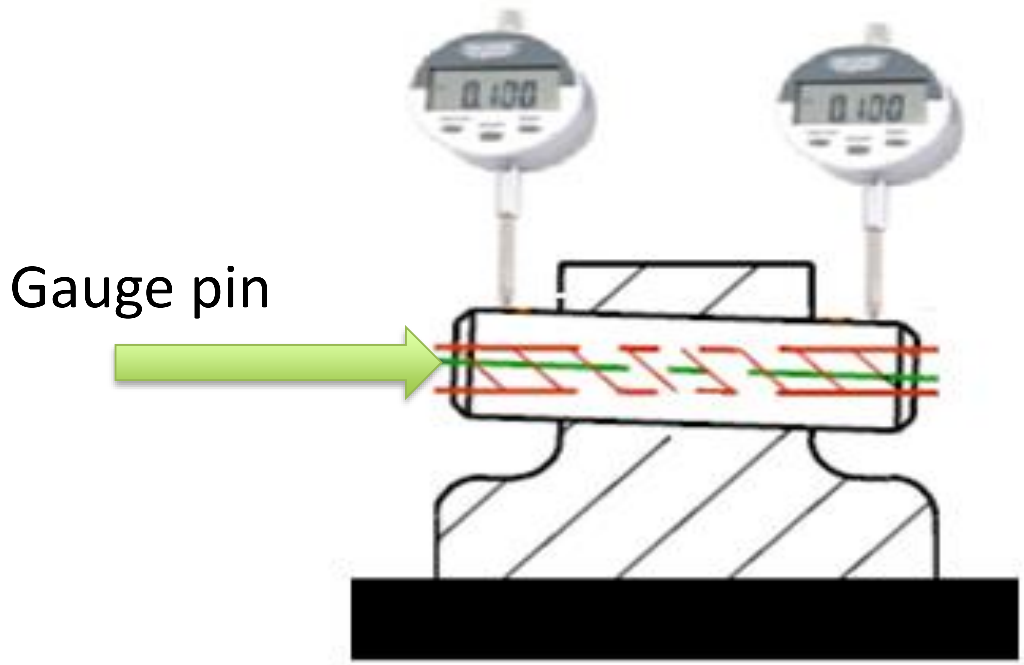
Reference surface, Supplementary datum.

Remember Abbe's Principle and the effects of bending moments.

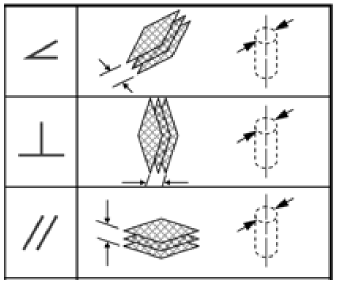
Gauge Pin Method



- Gauge pins located in bore as a supplementary datum.
- Height gauge can be used as an alternative to DTI.



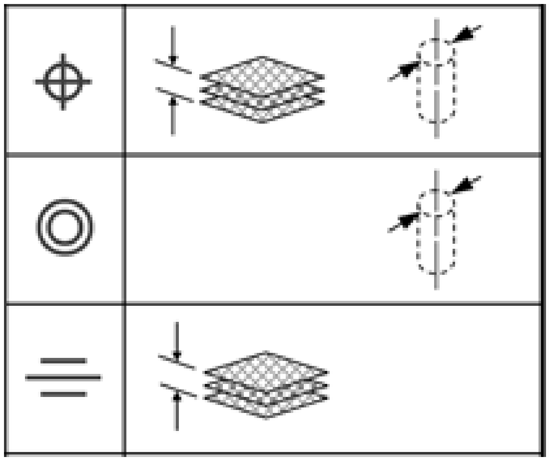
Orientation with CMM



- Angularity.
  - Creates best fit planes, lines or axes and records the deviations from these relative to a specified theoretical feature.
- Perpendicularity.
  - Creates a theoretical perpendicular plane relative to measured points and then compares the deviation of measured points relative to this plane.
- Parallelism.
  - Create best fit plains from measured points.
  - The difference between planes within the extents of the measured area is then recorded.

Location Tolerances

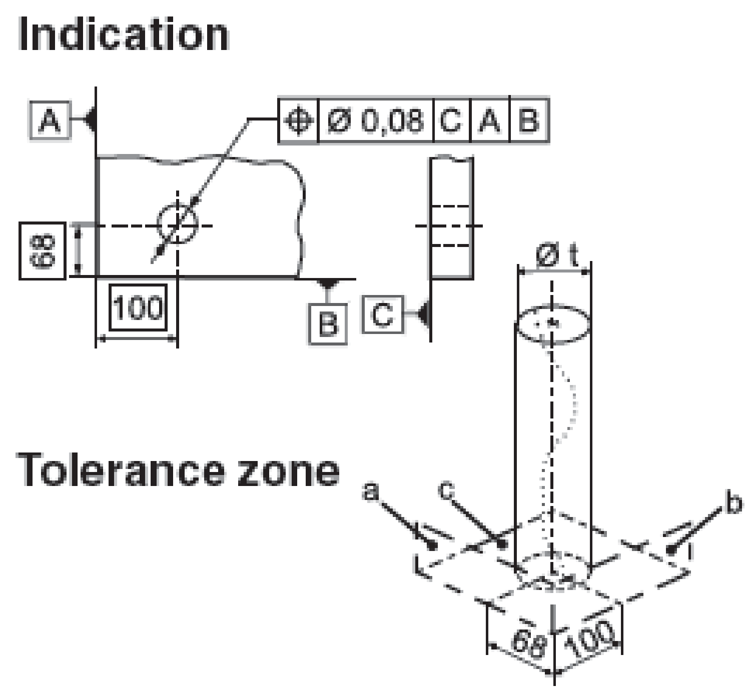
- Positional.
- Concentricity (Coaxiality).
- Symmetry.



Position

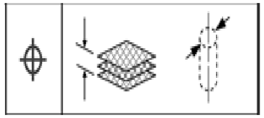
At least one datum must be referenced.
MMC or LMC can apply to a feature of size.

The extracted (actual) median line shall be within a cylindrical zone of diameter 0,08, the axis of which coincides with the theoretically exact position of the considered hole, with respect to datum planes C, A and B.

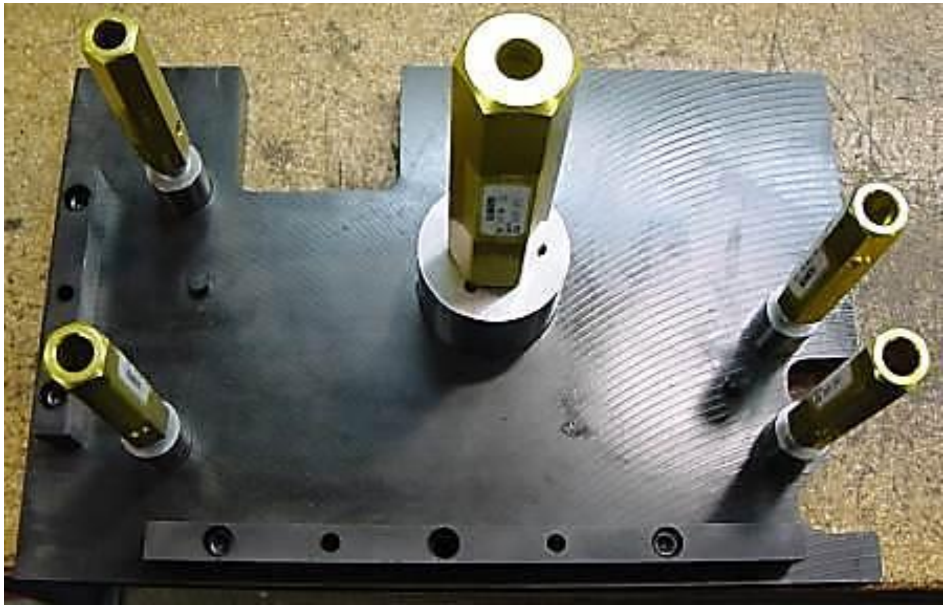


Courtesy of HEXAGON METROLOGY

Hard Gauging



- Confirm part conformity.
- Qualitative .
- Quick.



Height Gauge Attachments

Mitutoyo Center-Finder

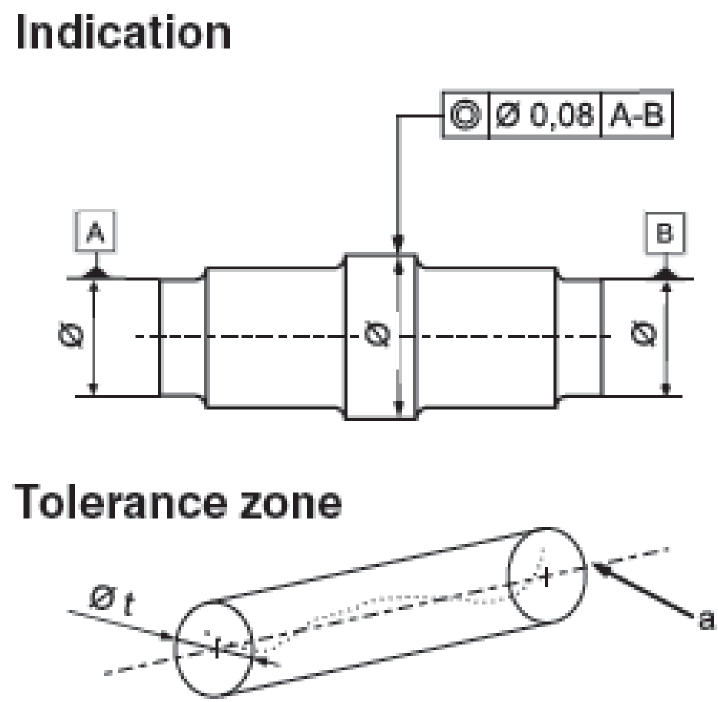
Depth Rod Attachment

Concentricity (Coaxiality)

2D 3D Feature At least one datum must be referenced.

Always regardless of feature of size, MMC and LMC cannot be applied.

The extracted (actual) median line of the toleranced cylinder shall be within a cylindrical zone of diameter 0,08 the axis of which is the common datum straight line A-B.

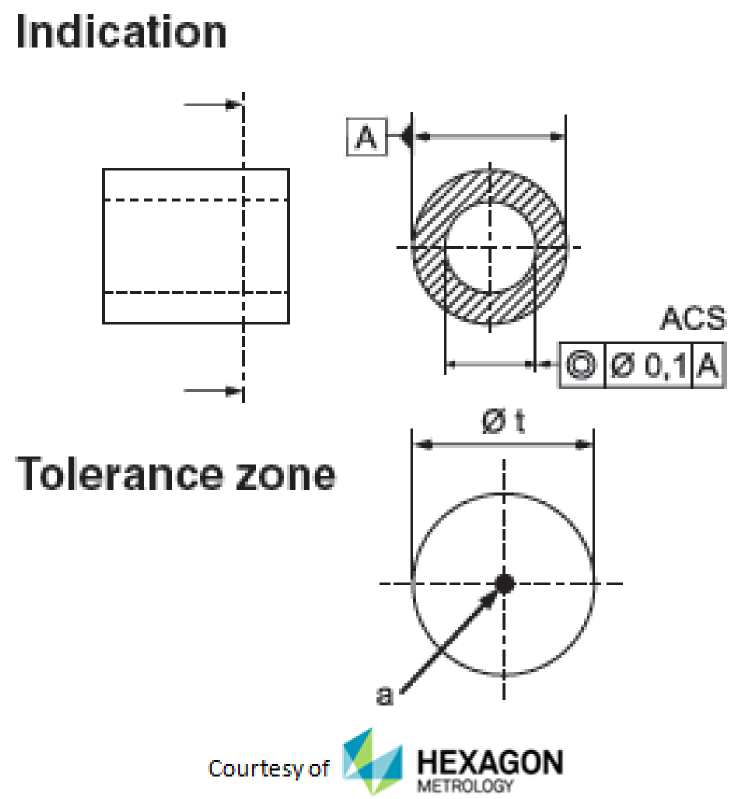


Courtesy of HEXAGON METROLOGY

Concentricity (Coaxiality)

2D 3D Feature At least one datum must be referenced.
Always regardless of feature of size, MMC and LMC cannot be applied.

The extracted (actual) centre of the inner circle shall be within a circle of diameter 0,1 concentric with datum point A in the cross-section.

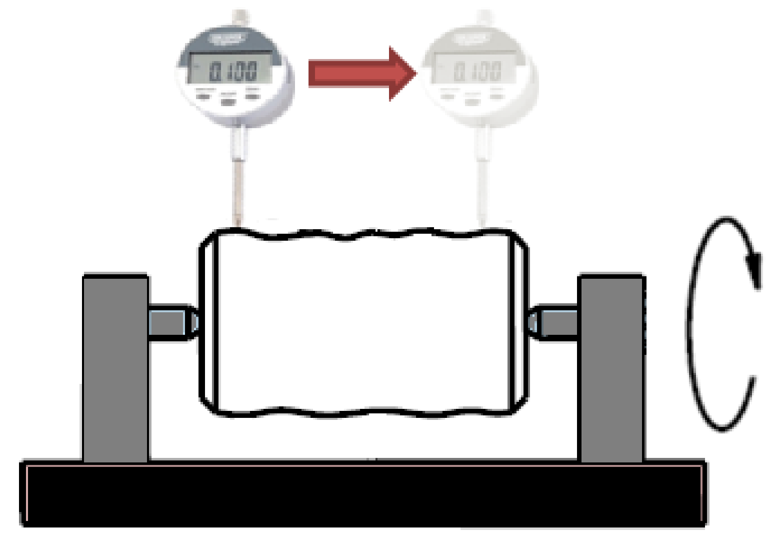


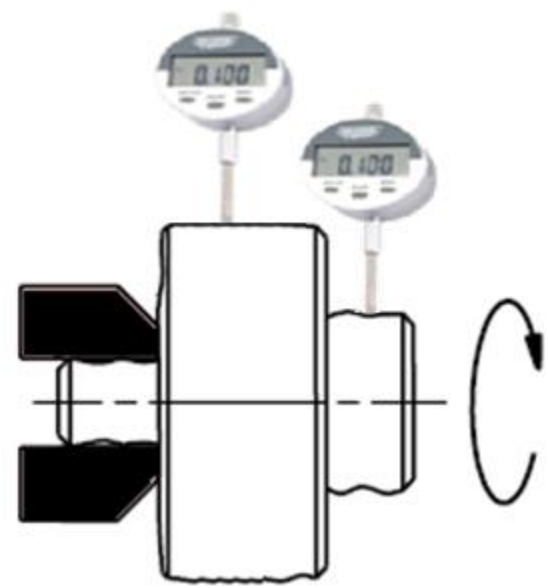
DTI Method

Fixture on the Datum.

- When centre line is the Datum, centres should be used.
- Face Datum, 3 Jaw chuck or V blocks should be used.

  Consider lobe effect when using V blocks.



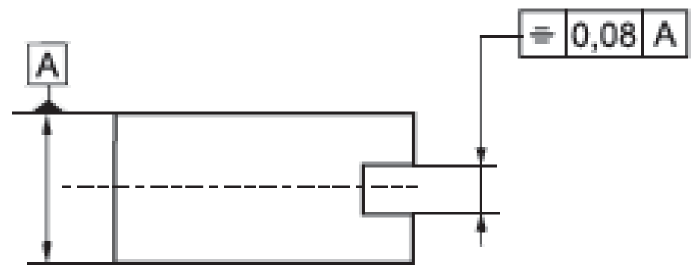


Symmetry

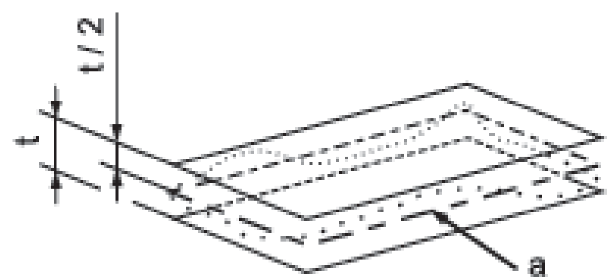
At least one datum must be referenced.
Always Regardless of feature of size, MMC and LMC can not be applied.

The extracted (actual) median surface shall be contained between two parallel planes 0,08 apart which are symmetrically disposed about the datum median plane A.

Indication

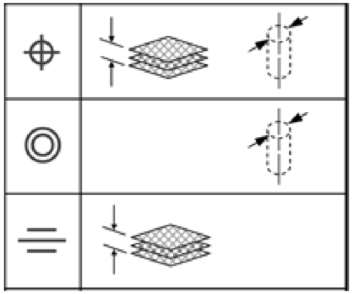


Tolerance zone



Courtesy of HEXAGON METROLOGY

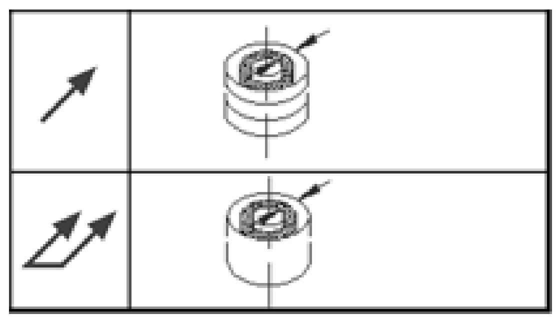
CMM



- Position.
  - Ideally suited to positional measurement. Feature to Feature and Feature to Datum relationship are easily determined.
- Concentricity.
  - Can be susceptible to arc fitting.
- Symmetry.
  - Can be susceptible to line and plane fitting.

Runout Tolerances

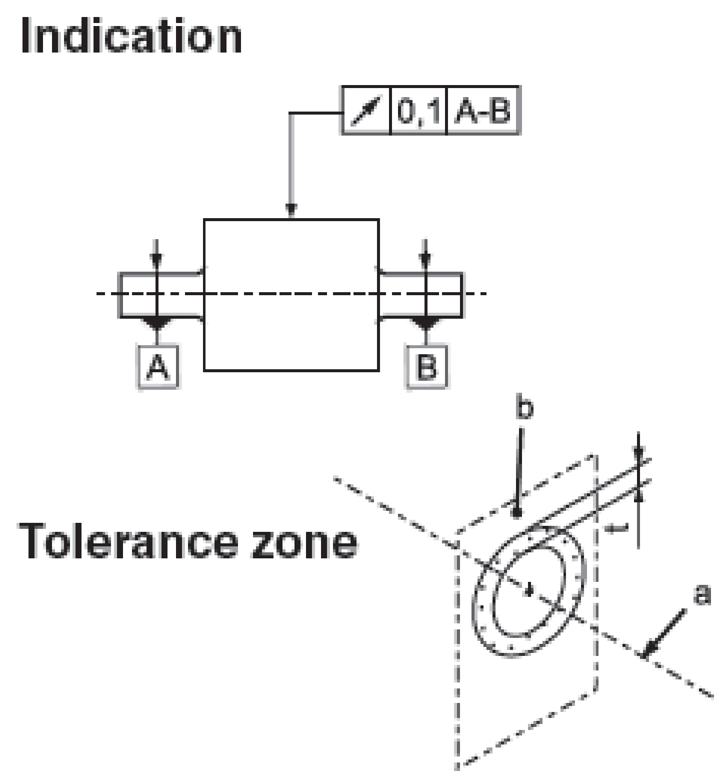
- Runout .
- Total Runout.



Runout

2D Feature At least one datum must be referenced.
Always Regardless of feature of size, MMC and LMC cannot be applied.

The extracted (actual) line in any cross section plane perpendicular to common datum straight line A-B shall be contained between two coplanar concentric circles with a difference in radii of 0,1.



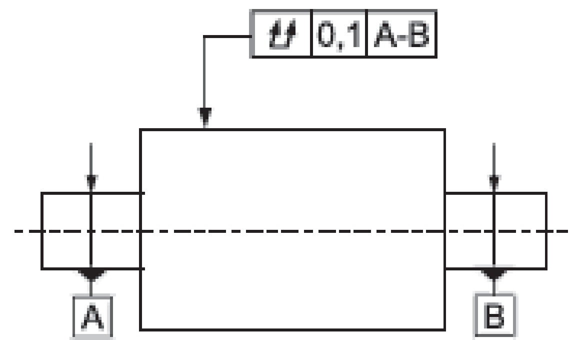
Courtesy of HEXAGON METROLOGY

Total Runout

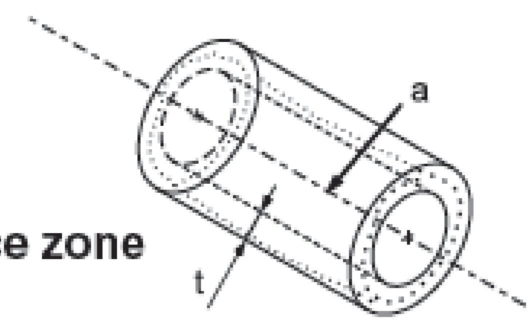
3D Feature At least one datum must be referenced.
Always Regardless of feature of size, MMC and LMC cannot be applied.

The extracted (actual) surface shall be contained between two coaxial cylinders with a difference in radii of 0,1 and the axes coincident with the common datum straight line A-B.

Indication

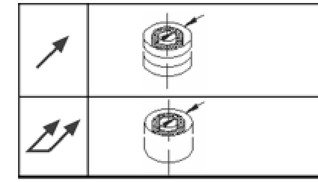


Tolerance zone



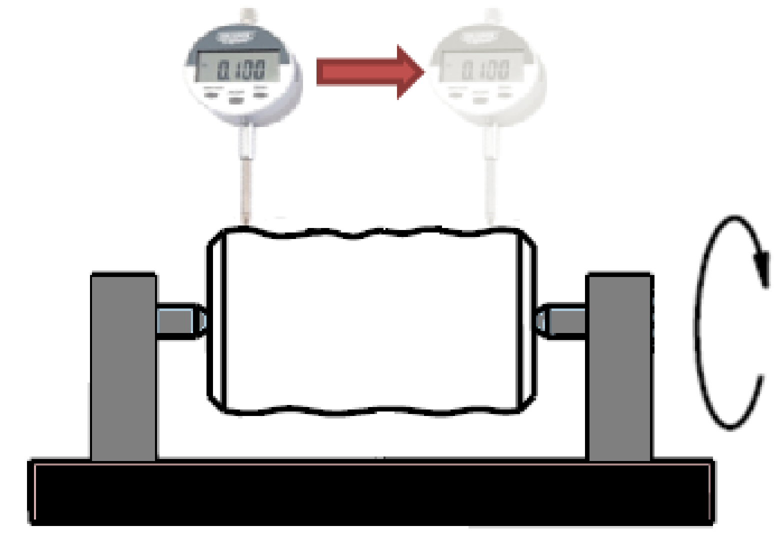
Courtesy of HEXAGON METROLOGY

DTI and Centers Method

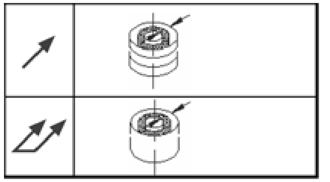


Using centres will be more robust however these need to be machined into the ends of the component. Tapers can also be used for hollow components.

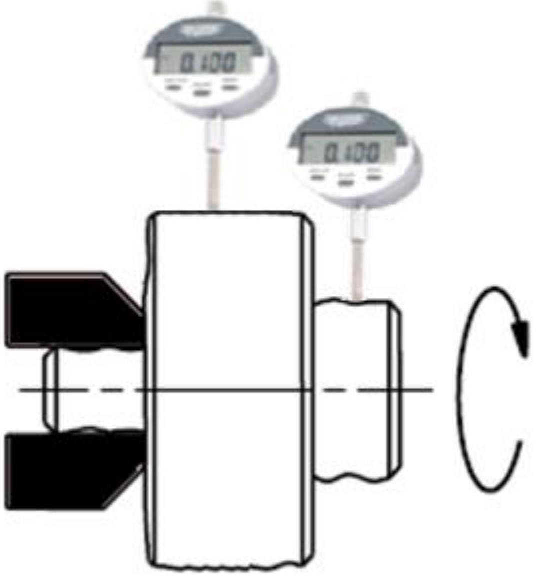
Runout includes concentricity errors and form Circularity errors



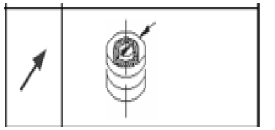
Fixture on the Datum face

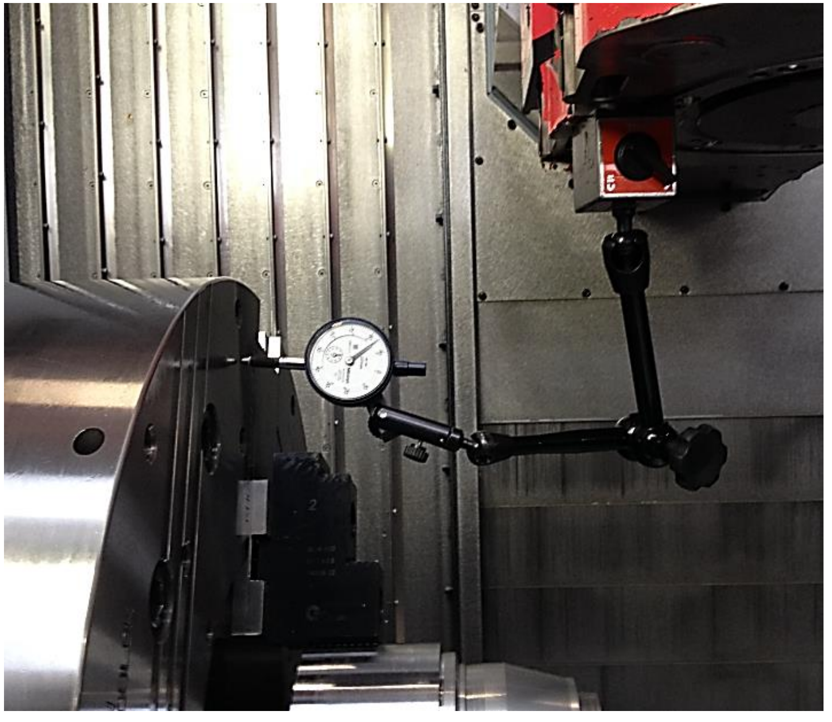


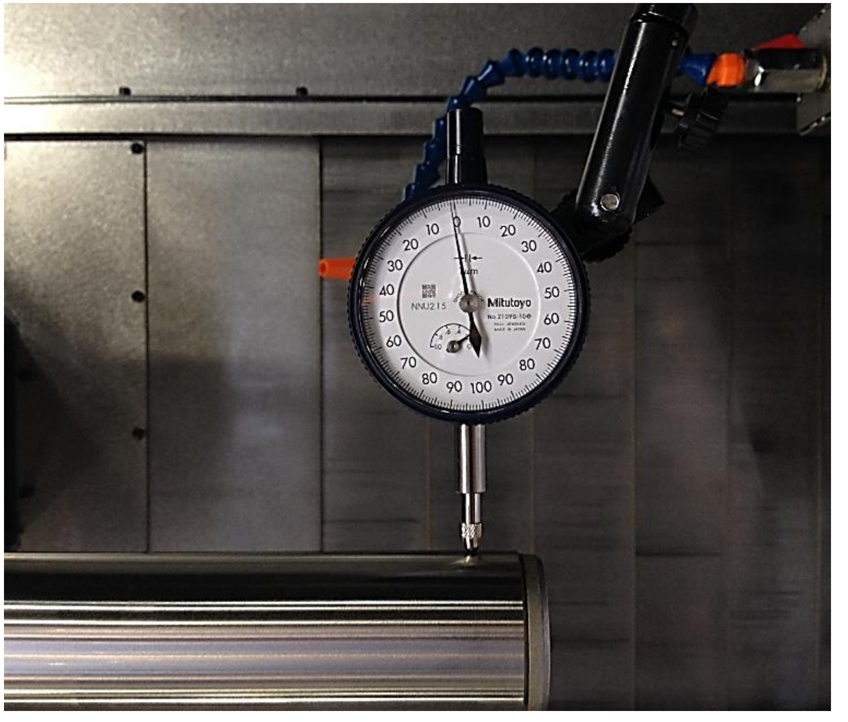
- Component held in a three jaw chuck at the datum face specified by the drawing detail.



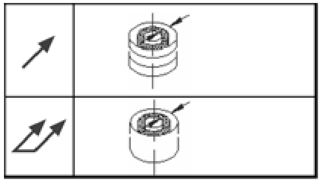
Radial and Axial Runout



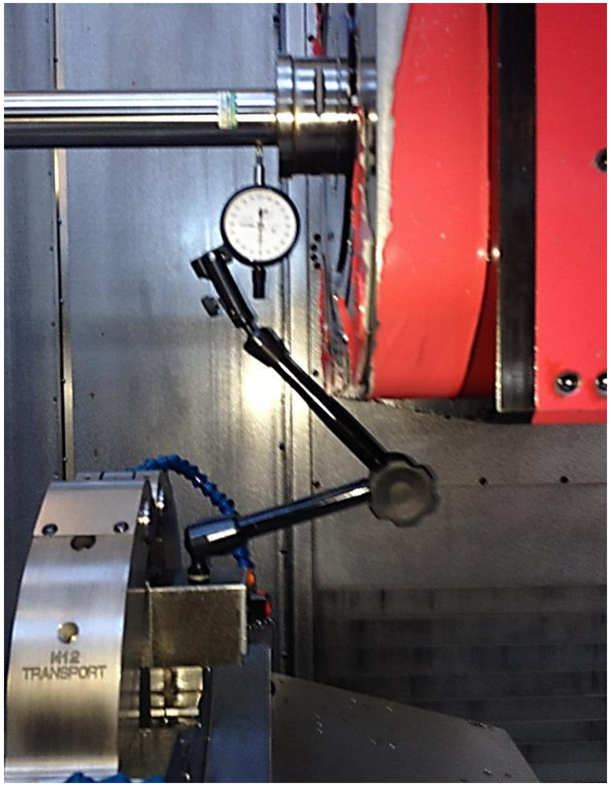




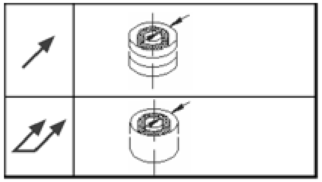
Measurement



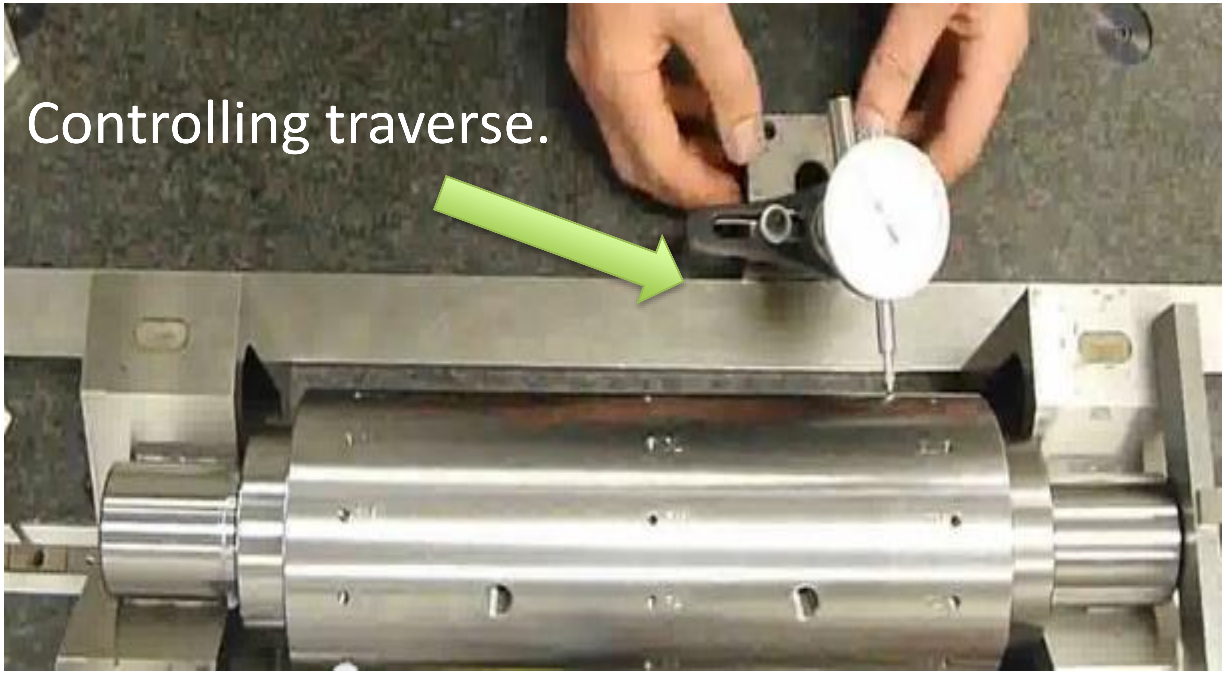
- Roundness Machine.
- In-Process on the lathe.



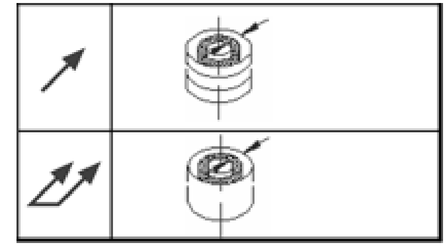
Measurement



- Control the linear traverse of the DTI.



Runout with CMM



- Runout and Total Runout the measurements can be achieved by CMM.
- The high density of points required can prove to be time consuming.
- CMM scanning probes are more practical, but be aware of the influence of scanning speed.

Gauges Transfer Instruments and Virtual Bodies

Basic Gauge Design Philosophies

- Accepts all conforming components, rejects all out of specification components and rejects a small percentage of borderline conforming components.

- Accepts all conforming components, rejects the majority of out of specification components and accepts a small percentage of borderline out of specification components.
- Accepts all conforming components and rejects the majority of out of specification components. Accepts a small percentage of borderline out of specification and rejects a small percentage of borderline conforming components.

Basic Gauge Design Principles

Product dimensional tolerances dictate the gauge tolerance; 5% is normally used.

Wear allowance typically 5% of the product dimensional tolerance.

- ***BS 969:1982 Limits and tolerances on plain limit gauges.***

Table 1 — Gauge size limits at 20 °C for ranges of workpiece tolerance (see Figure 1)

1	2	3	4	5	6	7
Workpiece tolerance Difference between high *(H)* limit and low *(L)* limit shaft or hole	Tolerance, *T*, for GO and for NOT GO gauges	Wear allowance, *W*, for GO gauges only	Plug type gauges [a]Limits expressed with respect to *H* minus *L* for the workpiece (hole)		Ring or gap gauges [b]Limits expressed with respect to *H* minus *L* for the workpiece (shaft)	
			GO	NOT GO	GO	NOT GO
mm	mm	mm	mm	mm	mm	mm
0.009[b] up to and including 0.018	0.001	0.001	$L^{+0.002}_{+0.001}$	$H^{+0}_{-0.001}$	$H^{-0.001}_{-0.002}$	$L^{+0.001}_{-0}$
Above 0.018 up to and including 0.032	0.002	0.001	$L^{+0.003}_{+0.001}$	$H^{+0}_{-0.002}$	$H^{-0.001}_{-0.003}$	$L^{+0.002}_{-0}$
Above 0.032 up to and including 0.058	0.003	0.002	$L^{+0.005}_{+0.002}$	$H^{+0}_{-0.003}$	$H^{-0.002}_{-0.005}$	$L^{+0.003}_{-0}$

Basic Gauge Design Principles

- **American National Standard Gagemakers Tolerances.**
- ***ANSI B4.4M-1981 (R1994)BS 969:1982 Limits and tolerances on plain limit gauges.***

Basic Size		Class ZM	Class YM	Class XM	Class XXM	Class XXXM
Over	To	(0.05 IT11)	(0.05 IT9)	(0.05 IT8)	(0.05 IT7)	(0.05 IT6)
0	3	0.0030	0.0012	0.0007	0.0005	0.0003
3	6	0.0037	0.0015	0.0009	0.0006	0.0004
6	10	0.0045	0.0018	0.0011	0.0007	0.0005
10	18	0.0055	0.0021	0.0013	0.0009	0.0006
18	30	0.0065	0.0026	0.0016	0.0010	0.0007
30	50	0.0080	0.0031	0.0019	0.0012	0.0008
50	80	0.0095	0.0037	0.0023	0.0015	0.0010
80	120	0.0110	0.0043	0.0027	0.0017	0.0011
120	180	0.0125	0.0050	0.0031	0.0020	0.0013
180	250	0.0145	0.0057	0.0036	0.0023	0.0015
250	315	0.0160	0.0065	0.0040	0.0026	0.0016
315	400	0.0180	0.0070	0.0044	0.0028	0.0018
400	500	0.0200	0.0077	0.0048	0.0031	0.0020

All dimensions are in millimeters. For closer gagemakers tolerance classes than Class XXXM, specify 5 per cent of IT5, IT4, or IT3 and use the designation 0.05 IT5, 0.05 IT4, etc.

Basic Gauge Design Principles

GO NO-GO one gauge limit allows the gauge to be inserted while the other limit does not.

GO limit - used to check the dimension at its maximum material condition.

NO-GO limit - used to inspect the minimum material condition of the dimension of interest.

Other considerations are:

- Frequency of use.
- Appearance.
- Cost.
- Should inspect as many features as practicable.

Taylors Principle!

Basic Gauge Design Principles

"Fixed Limit Gauges" provide an accurate, quick & economical inspection of product specifications.

Gauging determines simply whether the part feature conforms to the design tolerance.

Gauging is normally faster than measuring, but does not provided information about feature of interest.

Typically manufactured from Chromed plate, tungsten carbide or ceramic.

Common Gauges

- Plug Gauge.
- Snap Gauge.
- Profile Gauge.
- Bore Gauge.
- Ring Gauge.
- Pin Gauge.
- Thread Gauge.
- Template.

ROK-IT Gauge

- Checks ovality roundness and diameter highly suitable for blind holes.

Special Gauges

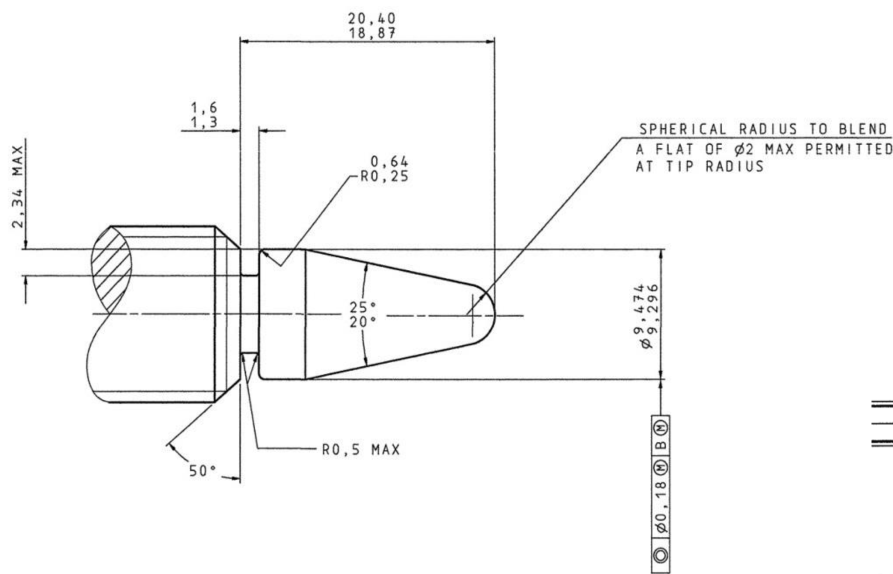
BOWERS GROUP

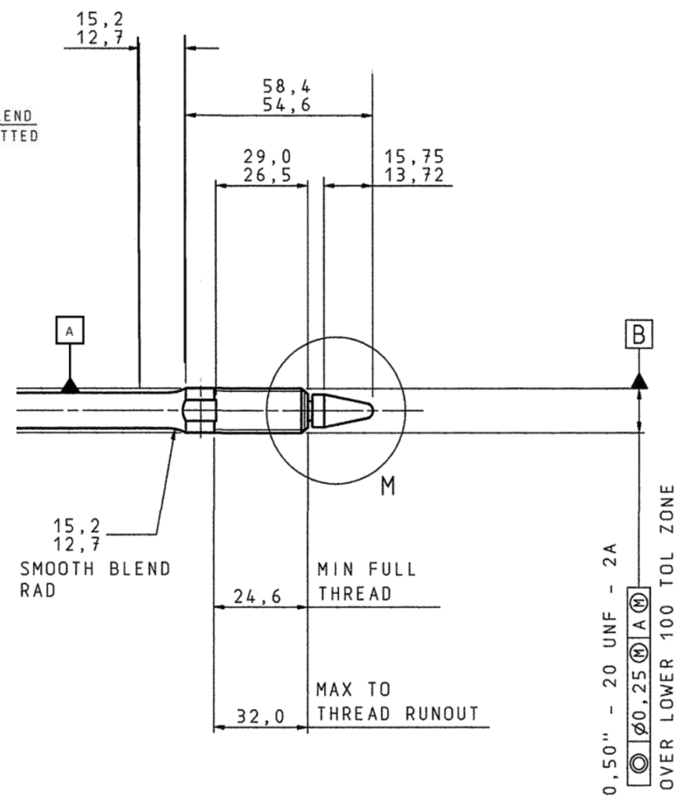
RENISHAW

Gauge Design Example

Westinghouse Non-Proprietary Class 3

- Sketch a basic Gauge Design to Check the Feature Highlighted below – Use Taylors principle to capture as many features as practicable.

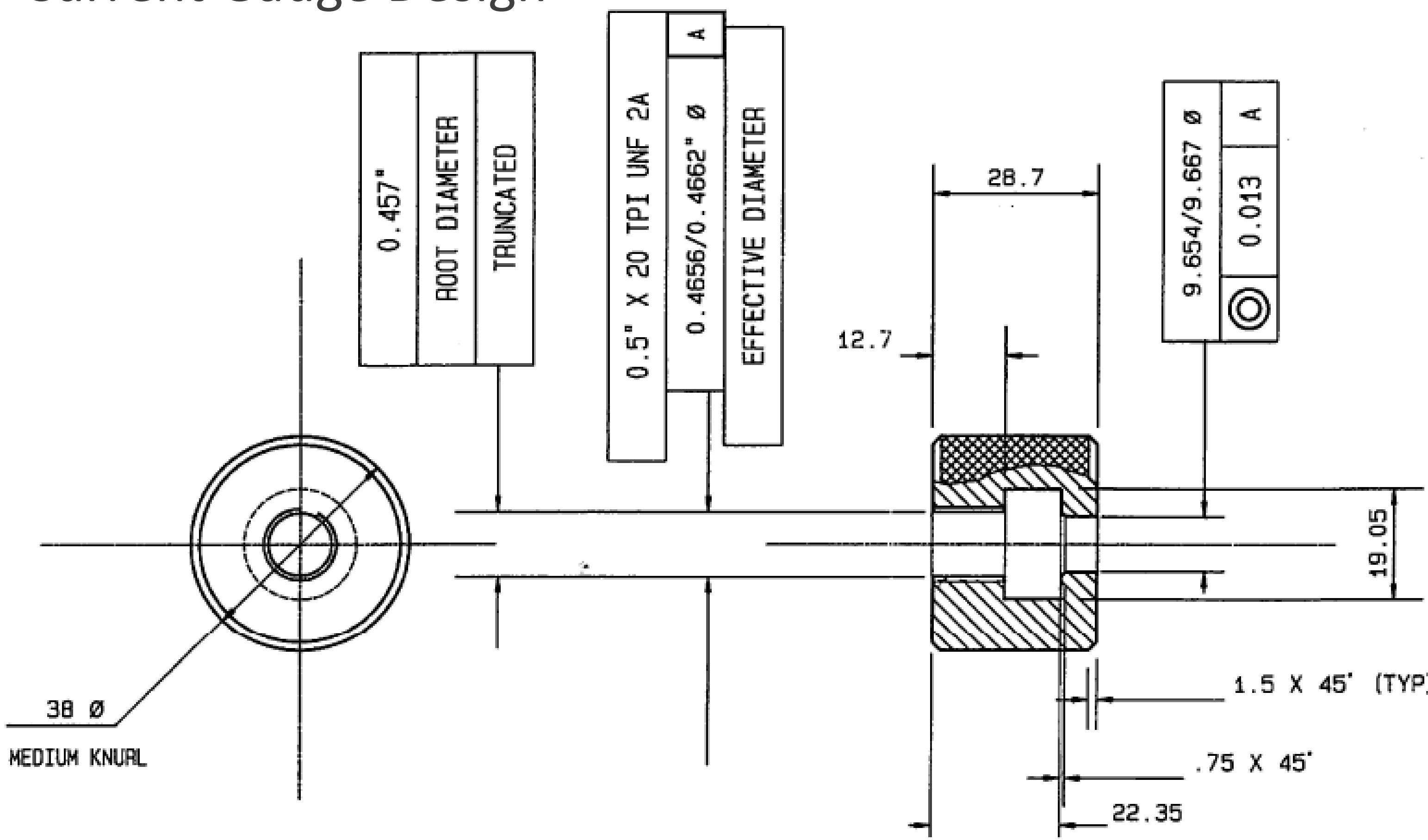




Gauge Design Example

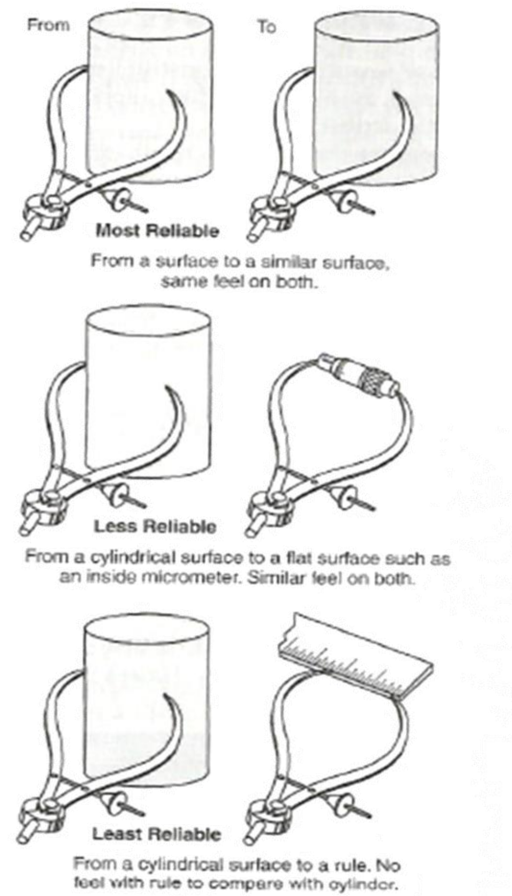
Westinghouse Non-Proprietary Class 3

- Current Gauge Design



Transfer Instruments

- Caliper.
- Feel is a major factor.
- Use a standard of similar form.



"Handbook of Dimensional Measurement" by Francis T Farago and Mark Curtis

Transfer Instruments

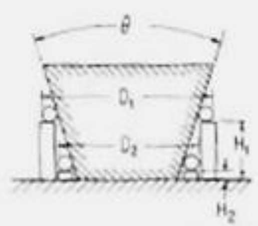
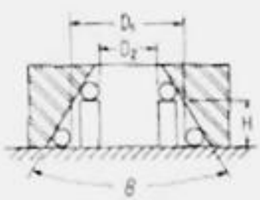
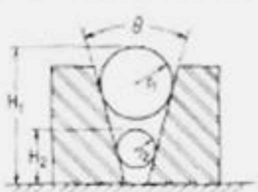
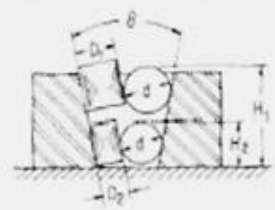
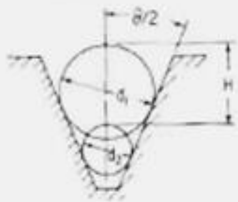
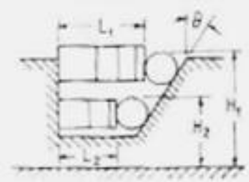
- Telescoping Gauge

Transfer Instruments

- Ball Gauge

Virtual Bodies

- Taper Inspection

The angle of a taper plug by the ratio of two diameters which are at a known distance apart		$\tan\frac{\theta}{2} = \frac{D_1 - D_2}{2(H_1 - H_2)}$
The angle of an internal taper by the ratio of two specific diameters		$\tan\frac{\theta}{2} = \frac{D_1 - D_2}{2H}$
The angle of a slender taper bore by the axial separation of two balls of known diameters		$\sin\frac{\theta}{2} = \frac{r_1 - r_2}{(H_1 - r_1) - (H_2 - r_2)}$
The angle of an internal taper by the axial separation of two balls, each leaning on a roller; all elements of known diameters		$\sin\frac{\theta}{2} = \frac{D_1 - D_2}{2(H_1 - H_2)}$
The angle of a Vee-groove by the axial distance between the top elements of two gage rollers		$\sin\frac{\theta}{2} = \frac{d_1 - d_2}{2H \cdot (d_1 - d_2)}$
Slope angle of a groove with one inclined and one vertical side, with balls or rollers leaning on gage blocks		$\tan\theta = \frac{H_1 - H_2}{L_1 - L_2}$

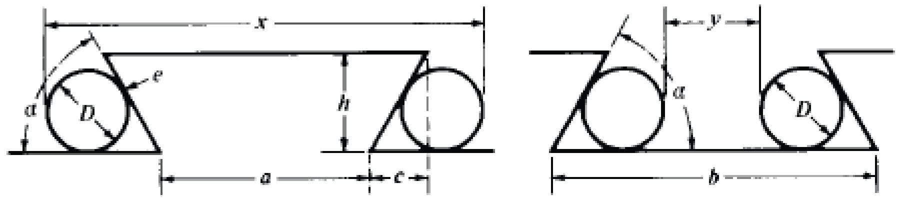
Handbook of Dimensional Measurement F. T. Farago

Virtual Bodies

- Tooling Ball Provides a constant datum

Virtual Bodies

- Dovetail and Slide Inspection



- Checking Radius of Arc by Measurement Over Rolls.

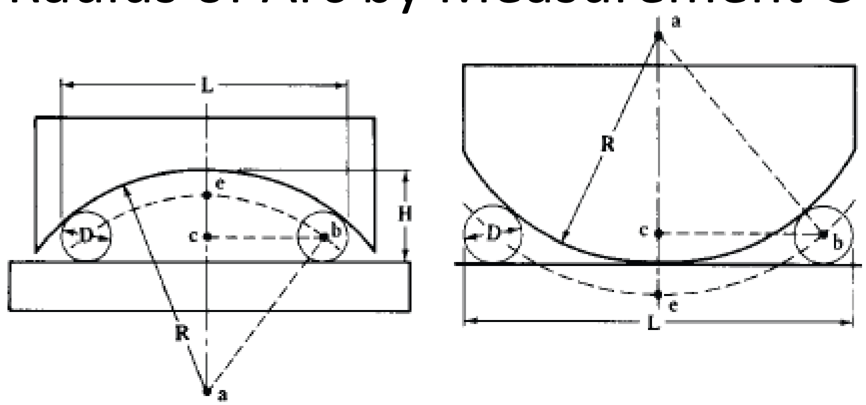


Fig. 3a. Fig. 3b.

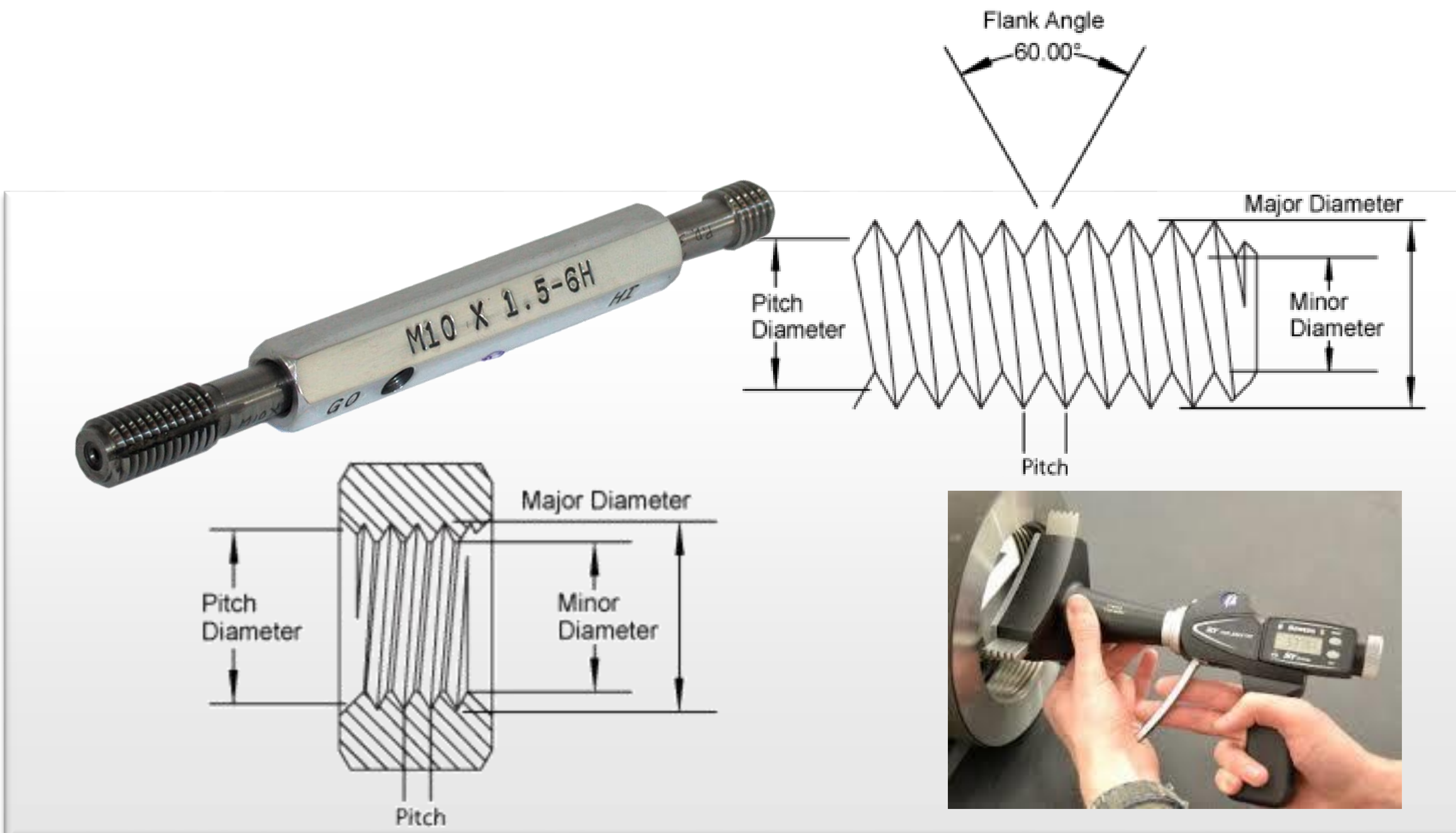
Machinery's Handbook 28th Edition

Virtual Bodies

- 3 Point Kinematic mount.

Improvise using sound engineering principles

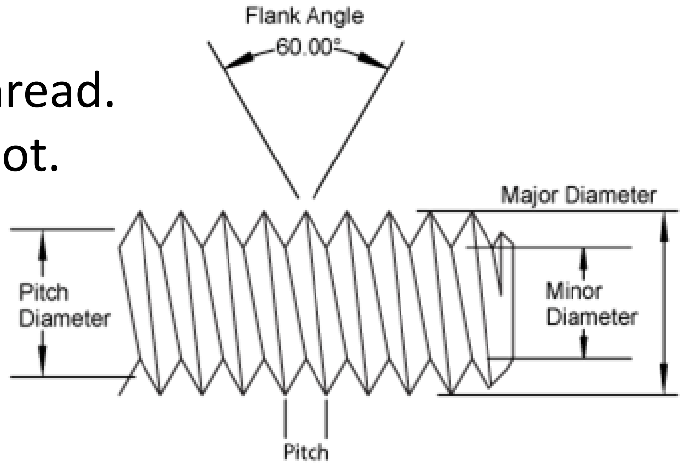
Threads


M10 X 1.5-6H
GO
HI
Flank Angle
60.00°
Major Diameter
Pitch Diameter
Minor Diameter
Pitch
Major Diameter
Pitch Diameter
Minor Diameter
Pitch

Thread Nomenclature

- Pitch: The distance measured from crest to crest or root to root.
- Lead: The distance moved by a nut or a bolt in axial direction in one complete revolution.
- Crest: The outer-most part of the thread.
- Root: The inner most part of the thread.
- Flank: The surface between the crest and the root.
- Angle of thread: The angle between the flanks.
- Depth: It is the distance between crest and root.
- Nominal diameter: The diameter of the cylindrical piece on which threads are cut is called.
- Major diameter: Diameter at the crest of the thread.
- Minor diameter: The diameter at the core or root.

Effective Diameter: An imaginary cylinder, which has equal metal and space widths. It is often referred to as pitch diameter.

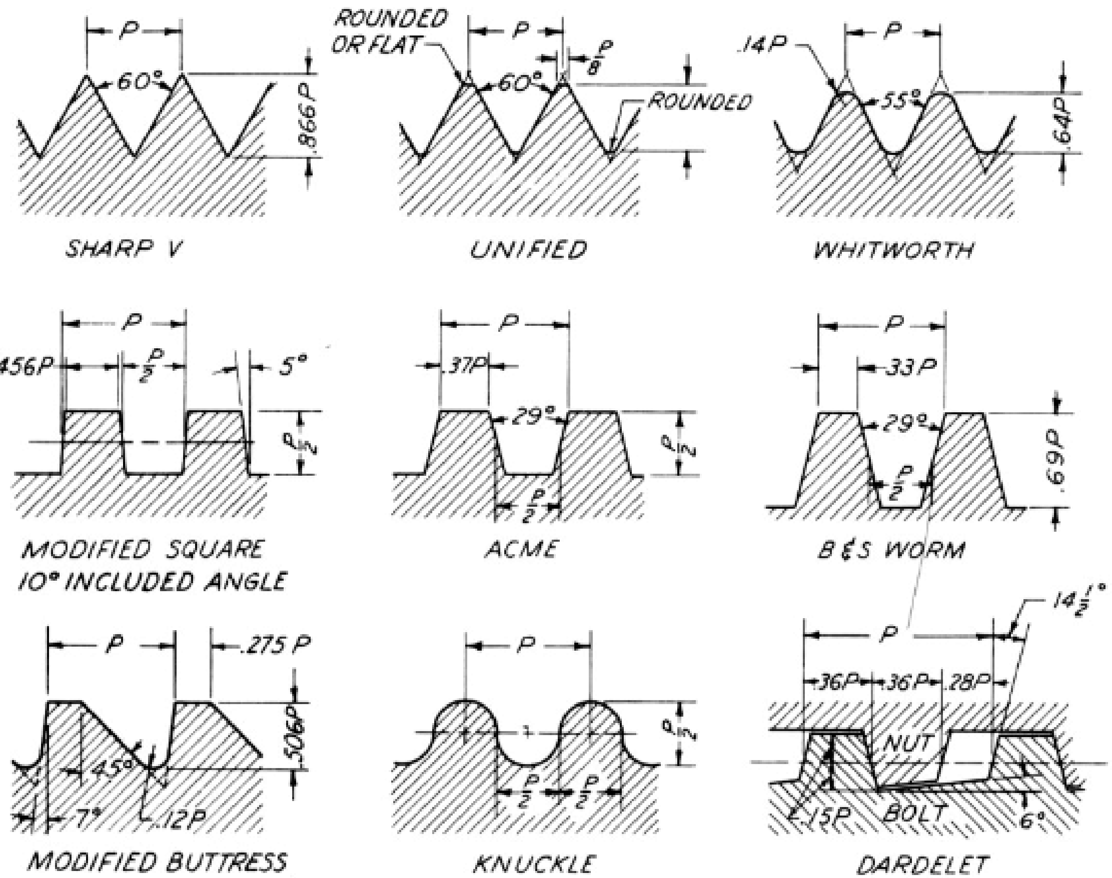


Common Thread Forms

Fixing

Load Bearing

Single Direction Load Bearing

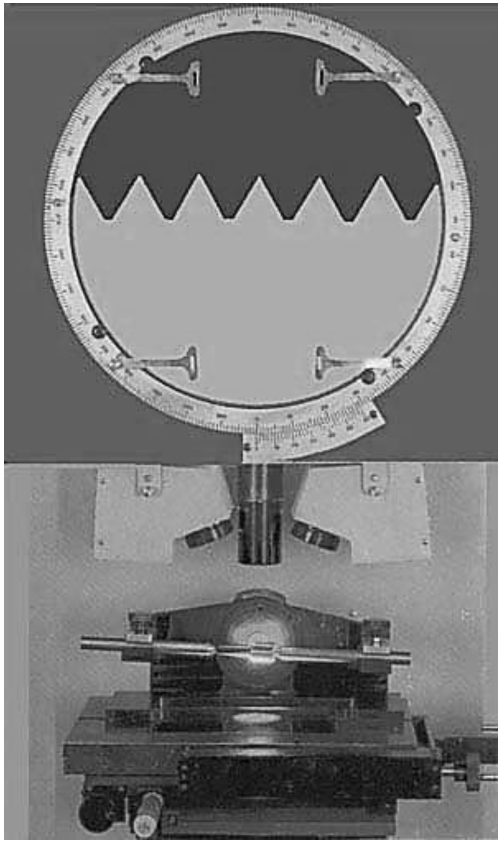


Shop Reference for Students and Apprentices, Second Edition

Thread Measurement

Profile Projection and Tool Makers Microscope inspect:

- Profile.
- Major and Minor Diameter.
- Angles.
- Form.



Thread Hard Gauges

Advantages:

- Inspects full thread profile and pitch.
- Can be used with a minimum of training.

Disadvantages:

- Only indicates if a thread is in specification.
- Time consuming when performing process control.
- Difficult/expensive to calibrate.
- Manufacturing and wear tolerances give less tolerance on the actual thread to be inspected.
- ***Templates indicate pitch errors and provide an indication of form errors.***

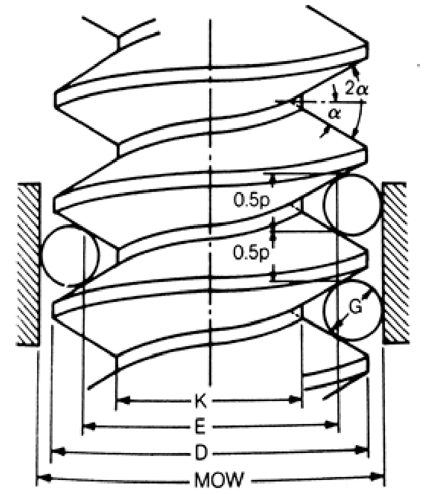
Three Wire Method

Advantages:

- Very accurate, assuming correct flank angle.
- Can be used on all external threads.
- Suitable for process control.

Disadvantages:

- Only inspects external threads.
- Requires a calculation to find the measurement result.
- Only measures thread pitch diameter.



Handbook of Dimensional Metrology F. T. Farago

Thread Measurement

Three wire method calculation

Wire selection calculation:

- Largest wire diameter 1.010 x P
- Optimal Wire diameter 0.57735 x P
- Smallest wire diameter 0.505 x P

Measurement over wires calculation:

M = D + 3G – 1,5155 x P

"D" Recoded diameter, "P" Pitch, "G" Diameter of the Wires

Thread Micrometer

Advantages:

- Accurate, assuming correct flank angle.
- Can be used on all threads with the same flank angle.
- Suitable for process control.

Disadvantage:

- Only suitable for external threads.
- Requires set-up/reference master when used with a micrometer larger than 25mm.
- Only measures thread pitch diameter.

Thread Gauge

Advantages:

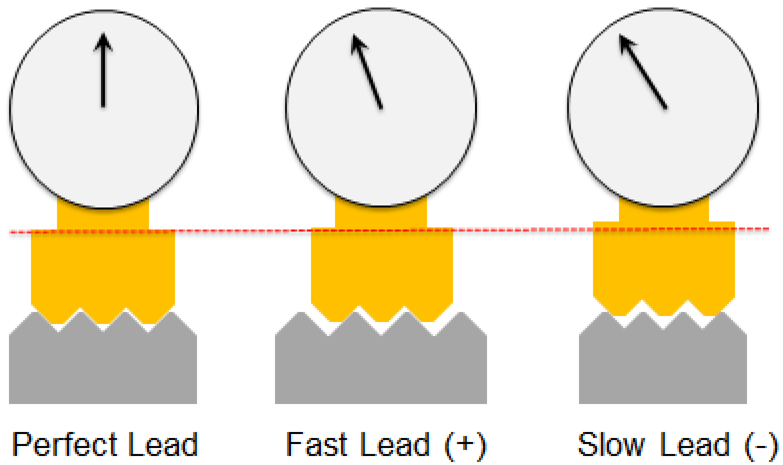
- Measures the total thread geometry (diameters and pitch).
- Possible for both external and internal threads.
- Thread gauge provide quantative measurement on tolerance.
- Suitable for process control.

Disadvantages:

- Can only be used for a specific thread.
- Requires a master for correct set up.
- One wrong dimension on the threaded component can give a false indication.

Effect of Lead on Pitch Diameter

The Diagram shows how lead can effect measurement of the effective pitch diameter. This same effect can occur with flank angle variation. As the pitch diameter nears its tolerance limits any lead angle error may not be detected. It is therefore essential to check the thread form and not just the pitch diameter.



CMM Inspection of Threads

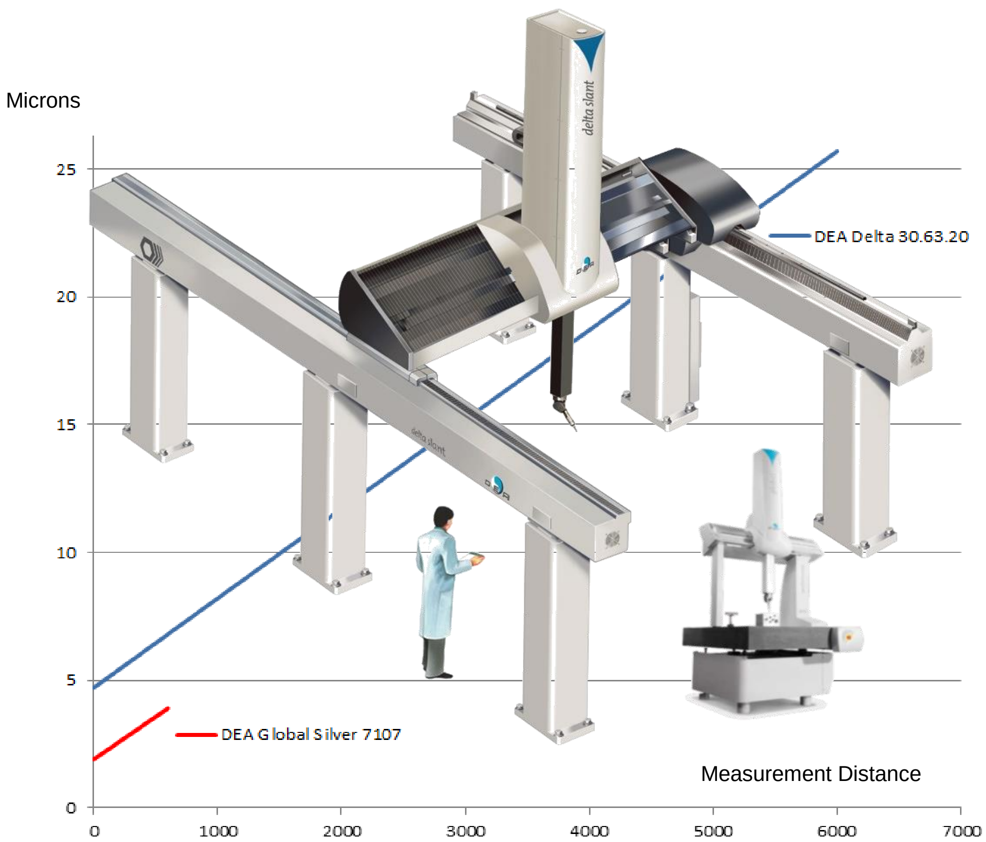
- Not an ideal instrument for inspection of threads.
- Capable for threads with pitch greater than 5mm is possible.
- Capable of checking Angles with limited repeatability.
- Major Minor diameter possible.
- Pitch and Pitch Diameter possible.
- Other features are not measureable.

Co-ordinate Measuring Machine

Three main configurations:

- Gantry.
- Bridge.
- Arm.

CMM Touch trigger probe



Images courtesy of Hexagon and Renishaw

Advantages:

- Proven technology.
- Accurate and repeatable.
- The gold standard.

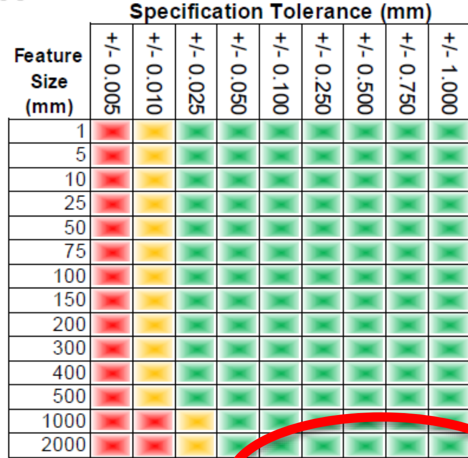
Disadvantages:

- Low point density.
- Relatively slow.
- Contact.
- Styli radius compensation.

CMM Instrument Capabilities.

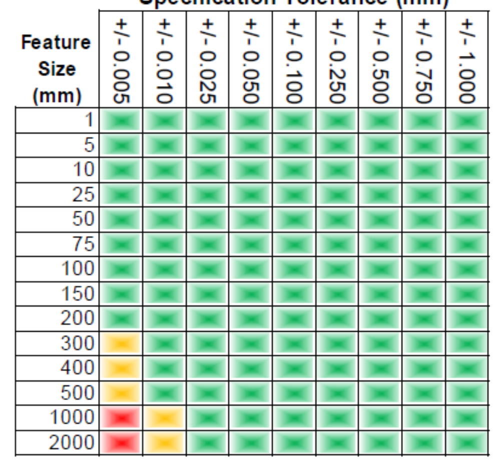
HEXAGON METROLOGY

Standard production CMM



Maximum Permissible Error of 2.3 + 0.3L/100 µm

High performance Measurement Laboratory CMM



MPE of 0.6 + 0.16L/100 µm

A typical Coordinate measuring machine precision before the introduction of styli length and fixtures has a range between 3µm and 10µm. A limited number of sub micron machine are available in the United Kingdom installed in laboratory conditions.

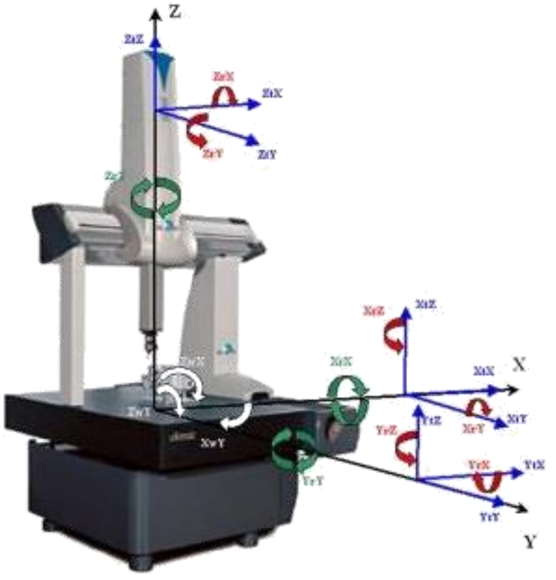
Reference Rolls Royce Guide to Dimensional Measurement Equipment Version 3.1.

CMM Good Practice- Setup

Machine errors are due to the manufacturing and assembly process and can contain 21 geometric errors. These errors include Roll, Pitch and Yaw, Straightness, Squareness and scale errors. Volumetric compensation is used to reduce these mechanical errors.

Reducing Uncertainty:

- Check the ‘calibration status’ of the CMM.
- Use a reverification artefact and perform interim checks to monitor drift. ISO10360
- Ensure CMM’s are calibrated and maintained regularly.



Courtesy of HEXAGON METROLOGY

Good Practice – Probe Setup

Correct probe qualification is vital to ensure accurate measurement.

Ensure that the reference sphere is calibrated, in good condition and its size is correctly referenced in the CMM software.

Before qualification, ensure reference sphere and stylus tip are clean and not loose.

Ensure qualification speed is the same as the planned measurement speed.

Re-qualify probes at regular intervals and always after a collision.

Good Practice – Probe Selection

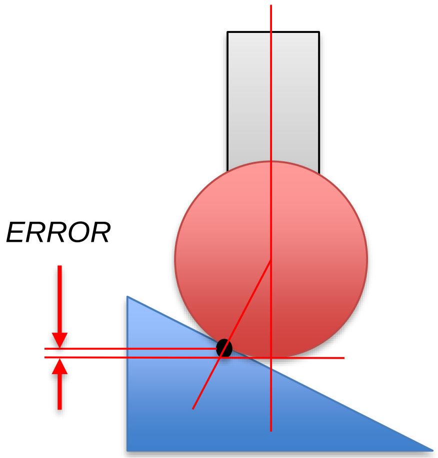
Use the shortest probe to increases the stiffness.

A large ruby eliminates any misalignment of the part to the probe, particularly when measuring deep holes and reduces the effect of surface roughness.

Styli can wear, so periodically check the tip and shank for signs of wear or damage.

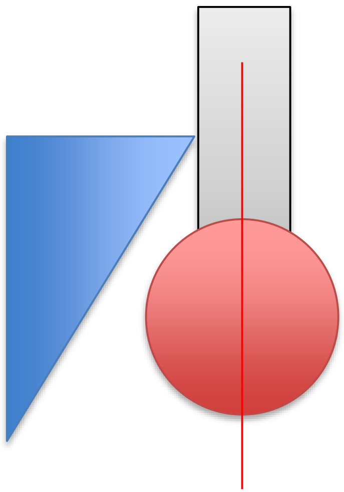
Minimise probe changes during measurement and indexing of the head.

CMM Good Practice - Probing



Approach surfaces using the correct vector to prevent cosine error. An angle of ± 20^{0} will avoid the probe skidding.

Decide on an optimum speed, approach distance and force. Excessive contact speed and force will have an effect on the measurement recorded.



During use, ensure that the tip of the stylus contacts the workpiece and not the shank, recording a false measurement.

Styli can attract debris, check for pickup.

CMM Good Practice

The distribution of points should depend on the tolerance, form, surface roughness. Choose the most economic number and distribution to achieve the most accurate result.

Geometric Feature	Mathematical Minimum	Recommended
Straight line	2	5
Plane	3	9
Circle	3	7
Sphere	4	9
Cone	6	12 or 15
Ellipse	5	12
Cylinder	5	12 or 15
Cube	6	18

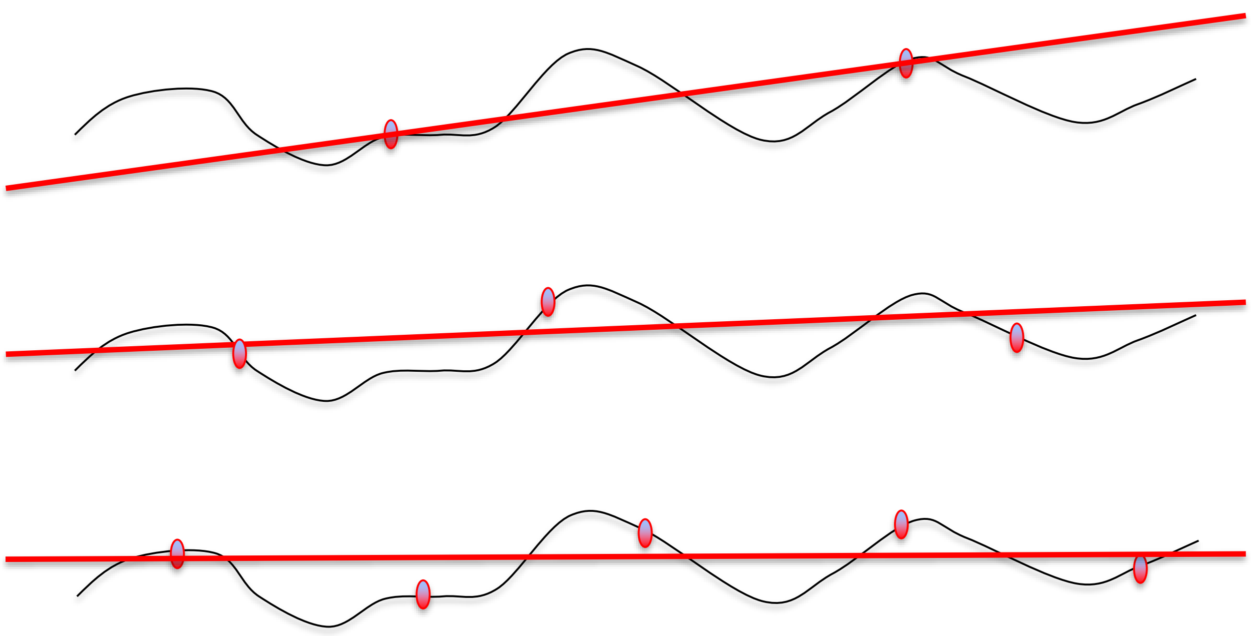
Choosing an ‘Ad Hoc’(see BS7172) distribution involving an odd and even number of points. This will provide more information on the form errors such as lobes.

Select the best algorithm for analysing the data. Best fit (least squares) is the normal software default.

Approach speed or scanning probe speed is critical.

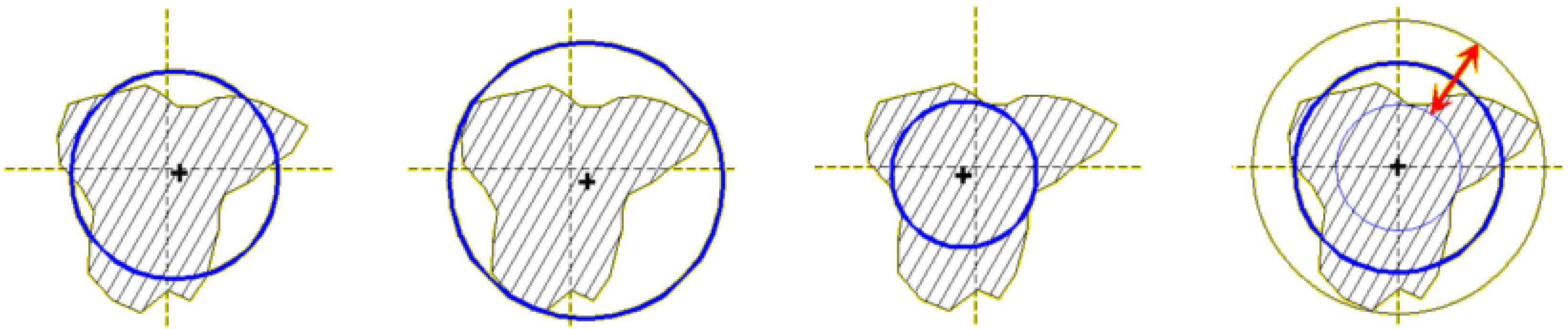
CMM Good Practice

Create Strong geometry - spread measurement points over largest possible area and use more than the minimum number of points. Essential for alignment feature.



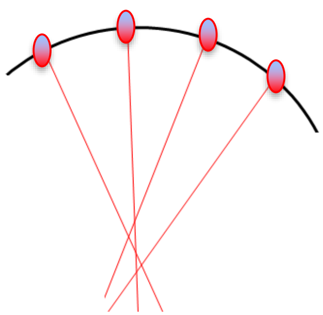
CMM Circle Fitting

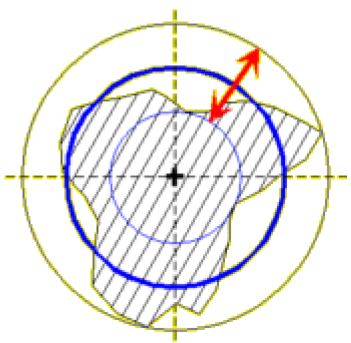
- Least square circle (LSC).
- Minimum circumscribed circle (MCC).
- Maximum inscribed circle (MIC).
- Minimum zone circle (MZC).



Partial Arcs >90^o

Because of the incomplete nature of the feature and the inherent form error it is very difficult to apply a best fit calculation as the radius centre is inconsistent.





Fit a circle that is equal to the specified radius and analyse the form errors.

Use Minimum Zone method that calculates two circles with a common centre, outside circle encompasses all points and the smaller inside all points.

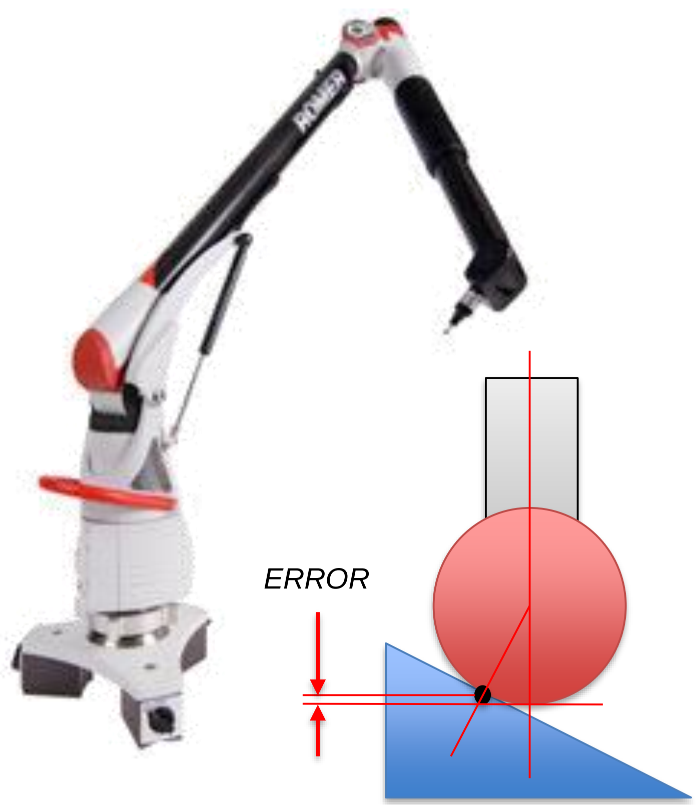
CMM Good Practice Filters

Software filters can be applied to eliminate unwanted points. Generated when scanning a circle to obtain roundness, A UPR filter will reduce the effect of surface roughness on the scanning probe that may result in larger roundness errors.

Remember that although filters can reduce unwanted data they can also remove useful data if applied too aggressively.

Check the specification requirements before applying filters.

Measurement Arms
Portable CMM



Point repeatability 42µm
Vol. Accuracy +/- 58µm

Advantages:

- Portable.
- Short learning curve.
- Moderate cost.

Disadvantages:

- Accuracy less than CMM.
- Data at probe tip’s centre.
- Manual operation.
- Accuracy influenced by operator.
- Not aware of the approach vector.

Introduction to the Measurement of Surface Texture

NPL
National Physical Laboratory

Recommend NPL guide

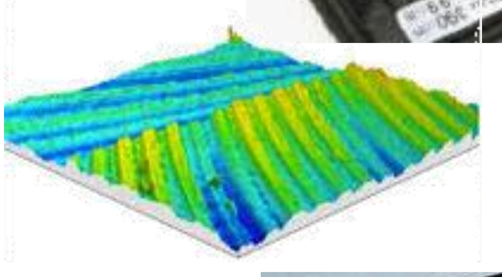
Richard Leach

Measurement Methods for Surface Roughness

Inspection and measurement of surface roughness can be carried out by different measurement instruments.

- Direct measurement methods (Stylus).

- Non contact methods (Optical).

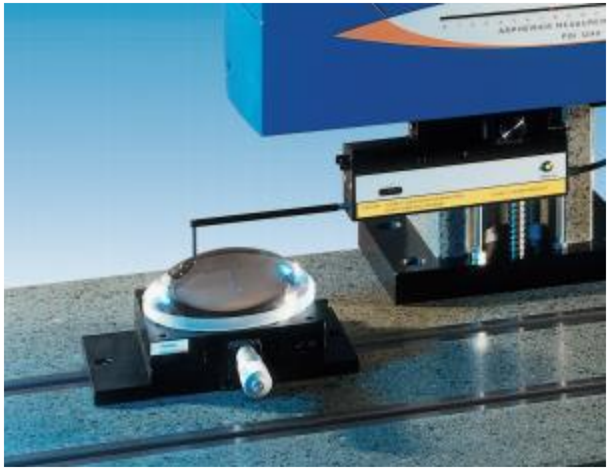


- Comparison based techniques.

Stylus Method

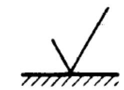
It is the most familiar and practical for the shop work environment.

Standards are available for the stylus method; although the standards are being developed for optical evaluation.



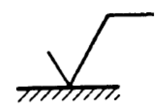
TAYLOR HOBSON®

Symbols and Definitions

Basic symbol used when its meaning is explained by a note. 

If the removal of material by machining. 

Removal of material is not permitted. 

Special surface characteristics required. 

Symbols and Definitions

a = Roughness value or grade number.

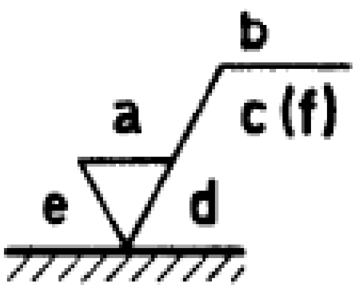
b = Production method.

c = Sampling length.

d = Direction of lay.

e = Machining allowance.

f = Other values.



Values and Grades

Roughness Ra µm	Roughness Grade
50	N12
25	N11
12.5	N10
6.3	N9
3.2	N8
1.6	N7
0.8	N6
0.4	N5
0.2	N4
0.1	N3
0.05	N2
0.025	N1

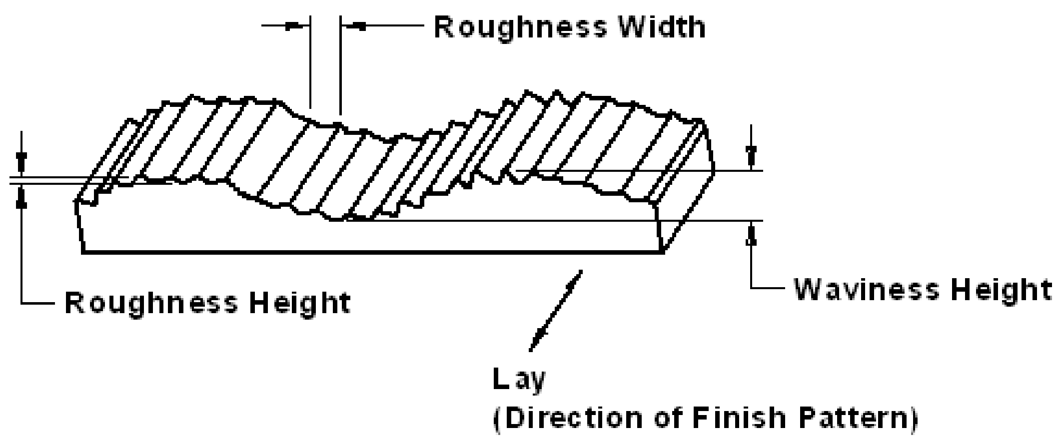
Terminology

Profile: Form of the profile reported by the instrument.

Roughness: The magnitude of the peaks and valleys.

Waviness: More widely spaced and may not be detected.

Lay: The direction of the peaks and valleys.



Cut Off Sampling Length

When the sampling length is indicated on the drawing or documentation the cut-off wavelength, λc, should be chosen to be equal to this sampling length.

The most commonly used sampling length is 0.8 mm.

	Cut-off wavelength/mm				
Process	**0.25**	**0.8**	**2.5**	**8.0**	**25.0**
Milling		✓	✓	✓	
Turning		✓	✓		
Grinding	✓	✓	✓		

Choice of cut-off wavelength for a number of common machining operations NPL Good Practice Guide No.37

Direction of Measurement

ISO 13565-1 indicates that the traversing direction for assessment purposes shall be perpendicular to the direction of the lay unless otherwise indicated.

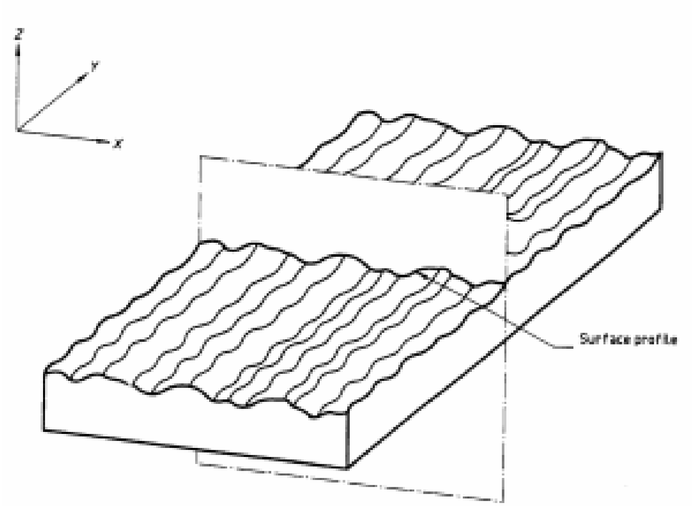
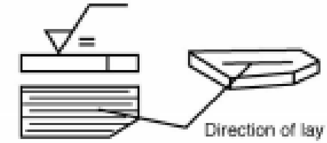
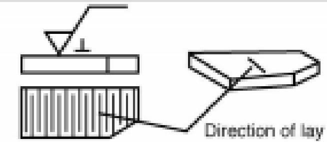
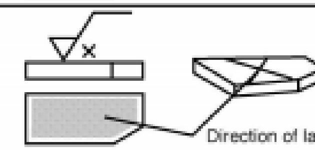
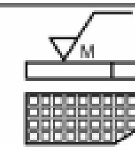
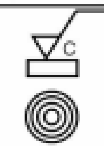
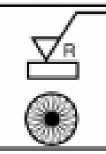
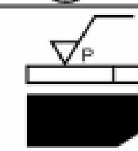


Figure 1 Co-ordinate system advocated by ISO 4287

Lay

Specified Direction of Measurement

ISO 1302

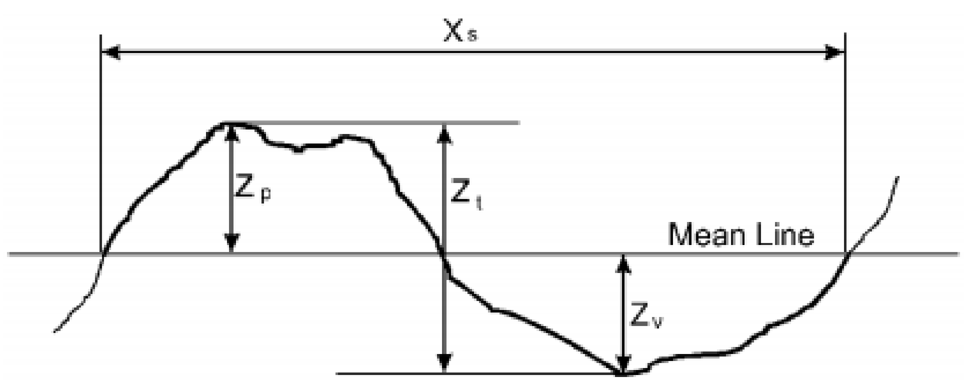
Graphic symbol	Interpretation and example	
=	Parallel to the plane of projection of the view in which the symbol is used	
⊥	Perpendicular to the plane of projection of the view in which the symbol is used	
×	Crossed in two oblique directions relative to the plane of projection of the view in which the symbol is used	
M	Multi-directional	
C	Approximately circular relative to the centre of the surface to which the symbol applies	
R	Approximately radial relative to the centre of the surface to which the symbol applies	
P	Lay is particulate, non-directional, or protuberant	
NOTE - If it is necessary to specify a surface pattern which is not clearly defined by these symbols, this shall be achieved by the addition of a suitable note to the drawing		

Measured Values

Profile peak height Zp is the distance between the mean line on the x axis and the highest point of the highest peak.

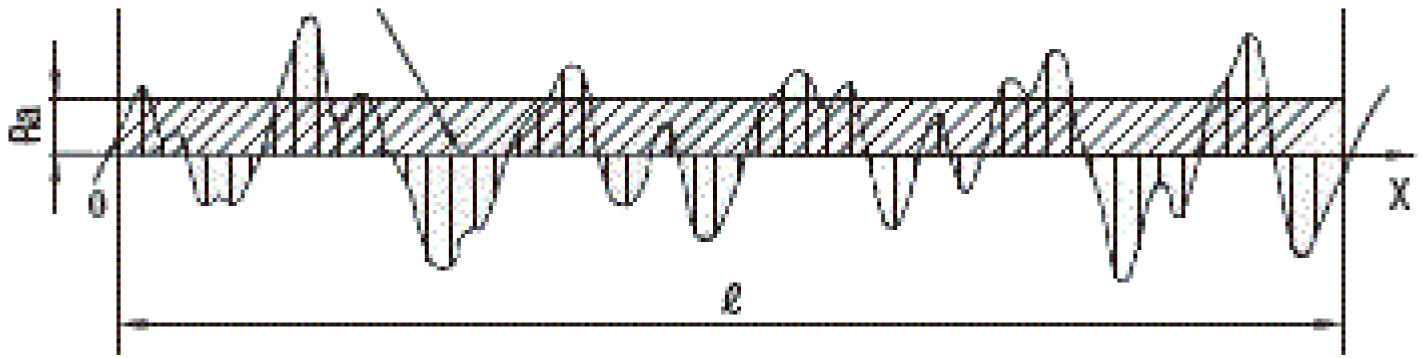
Profile valley depth Zv is the distance between the mean line on the x axis and the lowest point of the lowest profile valley.

Profile element height Zt is the sum of the height of the peak and depth of the valley.



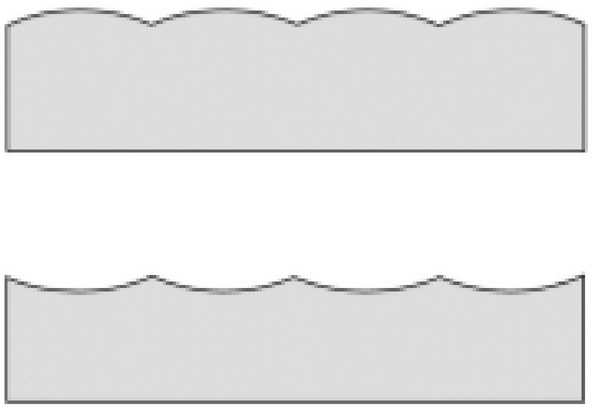
Arithmetical average roughness (Ra)

Ra is the arithmetic average of the absolute values.



Interpretation of Measurement

Consideration should be made with interpretation of measurements. Two surfaces may have the same surface texture Ra value, however they may have different functional characteristics.



Rubert Comparator

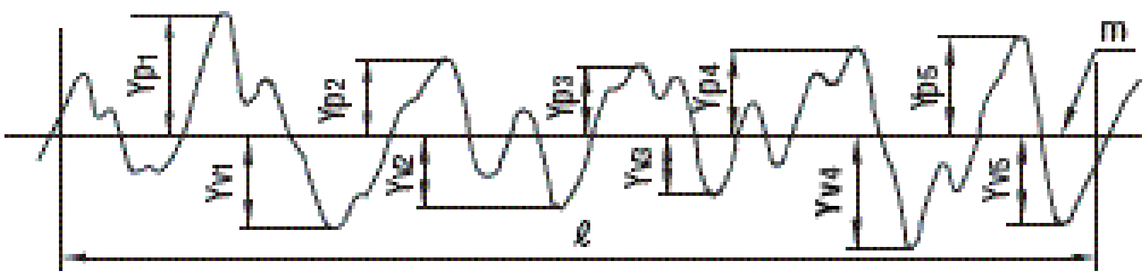
Commonly used to determine surface roughness

One Ra value can have very different surface characteristics and feel.

Alternative Surface Roughness Measures

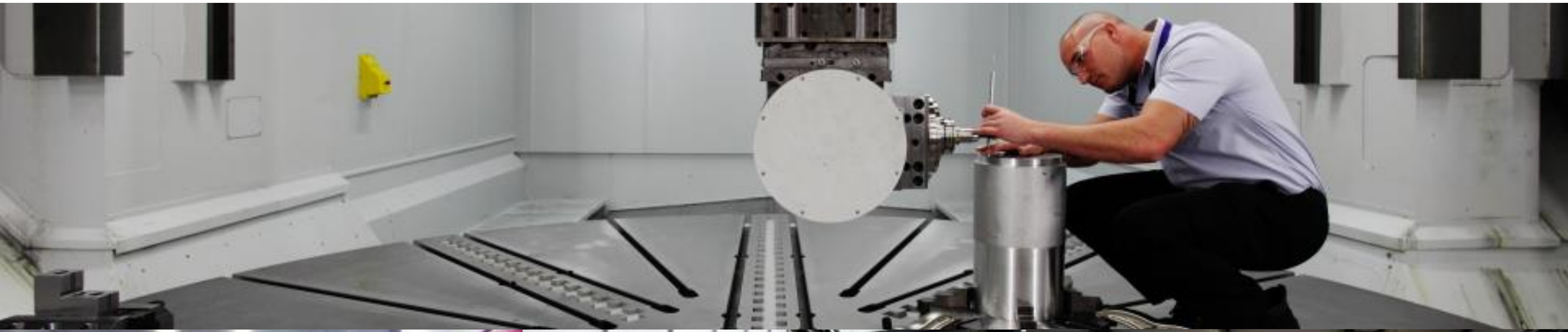
Ten-spot average roughness (Rz)

Averages the distance between the five peaks and five deepest valleys within the sampling length.

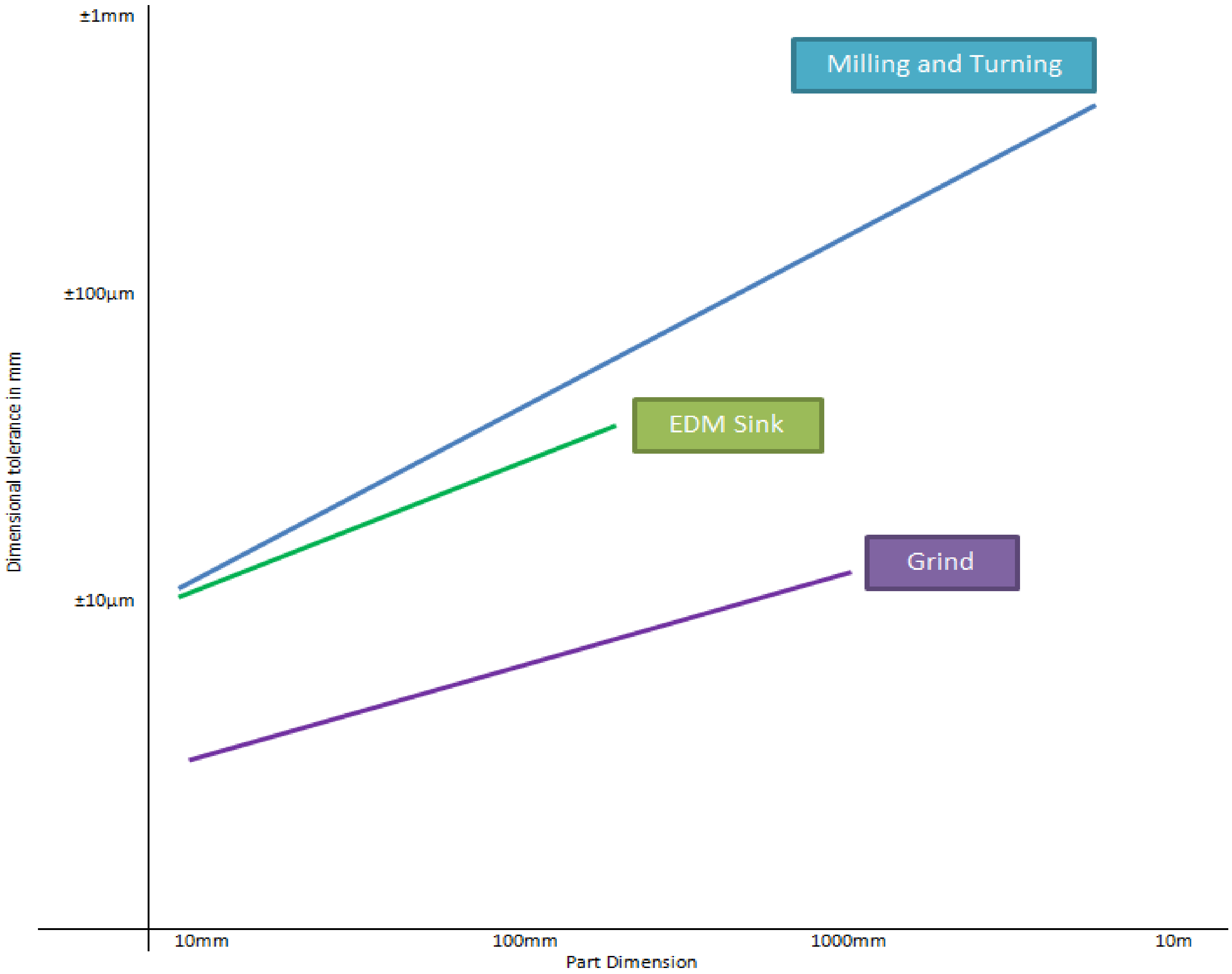


Other measures exist but are not covered in this introduction.

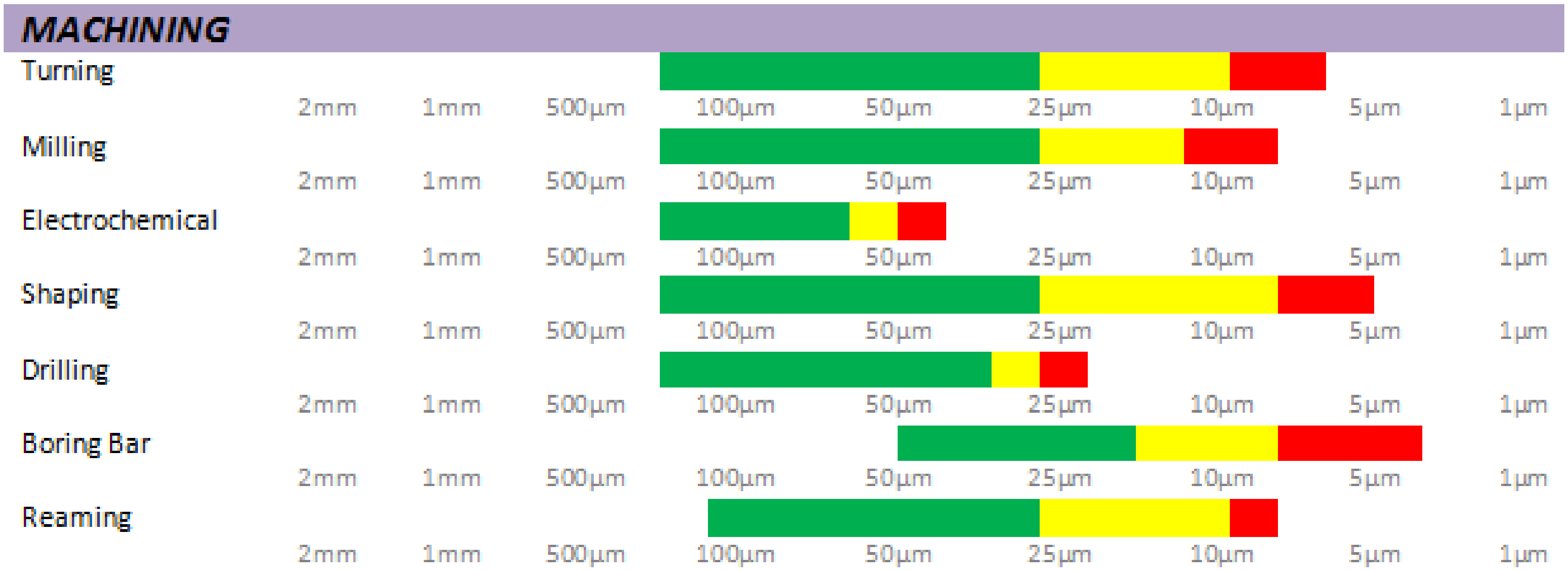
Manufacturing Process Capabilities



Typical Process Tolerance of Standard Production Machinery with Respect to Feature Size:

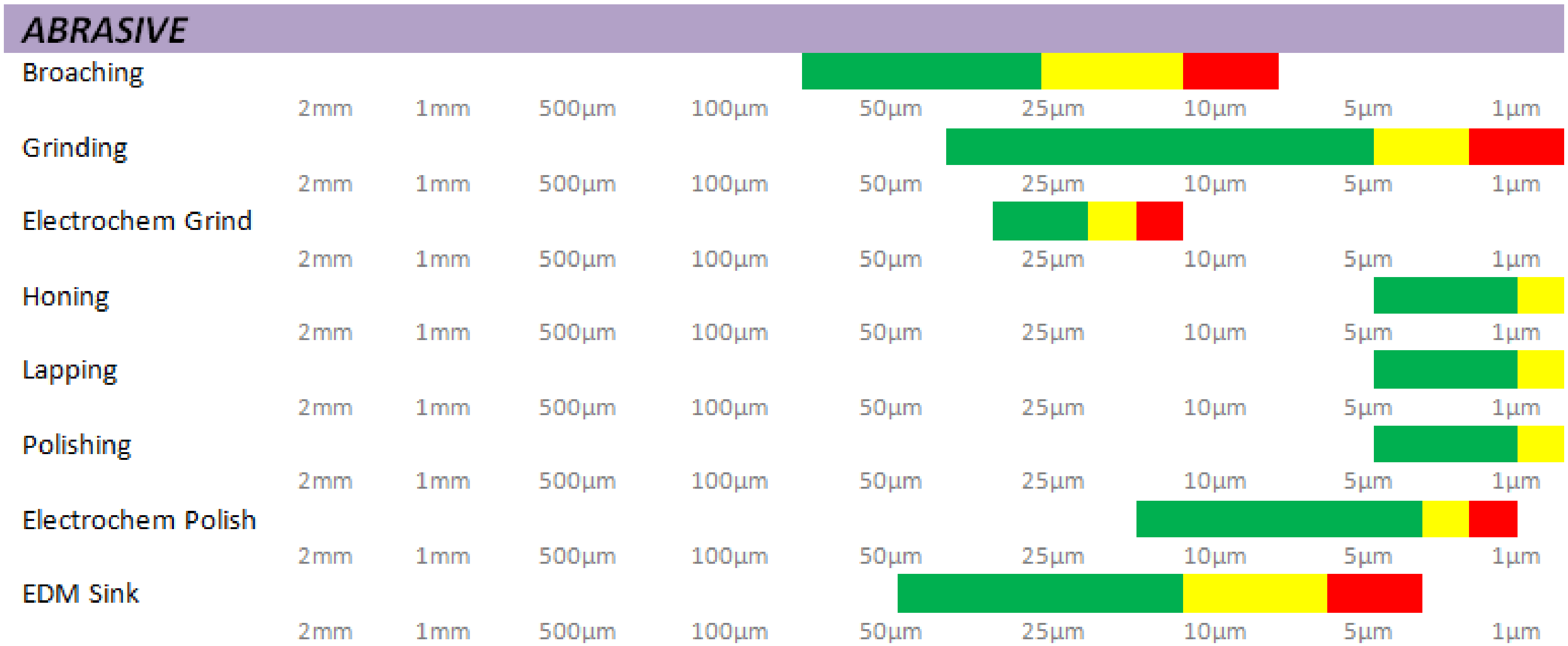


Typical Process Tolerance for Components up to 500mm:



The tolerance values depicted in this document are typical of the capabilities of precision manufacturing available in the supply chain and based on components of less than 1 meter in size. High precision facilities within environment controlled facilitates are not represented.

Typical Process Tolerance for Components up to 500mm:



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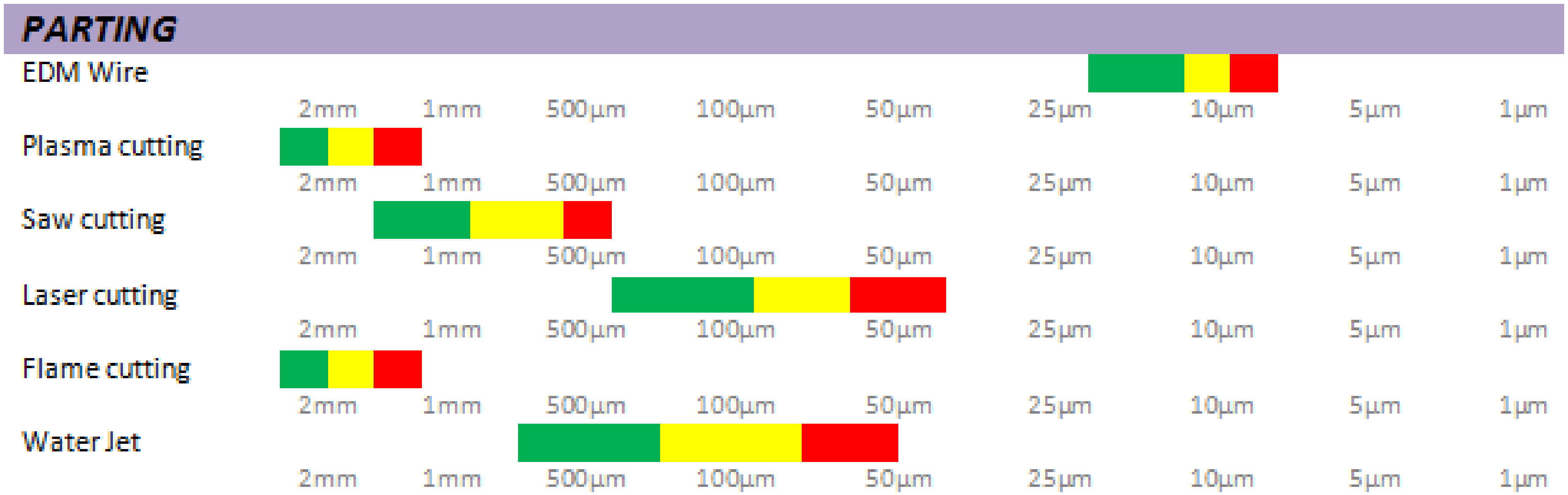
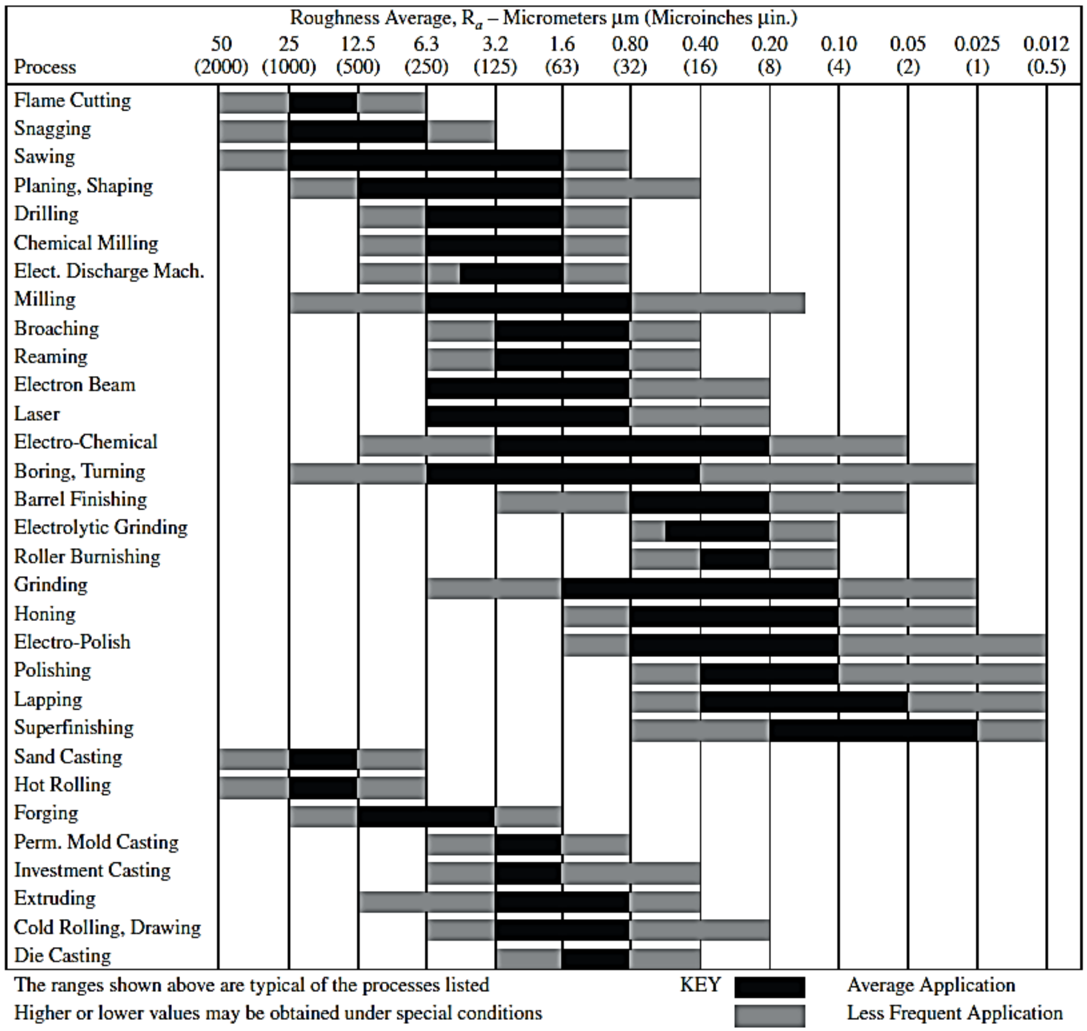


Please note that for parting technologies the figures apply to a 100mm section thickness.

The tolerance values depicted in this document are typical of the capabilities of precision manufacturing available in the supply chain and based on components of less than 1 meter in size. High precision facilities within environment controlled facilitates are not represented.

Surface Roughness Manufacturing Processes



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Recommended Reading

- “Fundamentals of Dimensional Metrology”
  - C. Dotson, R. Harlow and R. L. Thompson
- "Handbook of Dimensional Measurement“
  - F. T. Farago and M. Curtis
- “Machinery’s Handbook”
  - Industrial Press
- “Metrology for Engineers”
  - J.F.W. Galyer and C. R. Shotbolt