ENGINEERING METROLOGY
(DIMENSIONAL METROLOGY)

SURFACR FINISH MEASUREMENTS

DEPARTMENT OF MECHANICAL ENGINEERING
ISFAHAN UNIVERSITY OF TECHNOLOGY

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Surfaces

- ✓ A surface is what we touch when we hold an object such as a manufactured part
- ✓ Nominal surfaces are representing the intended surface contour of the part
- ✓ The nominal surfaces appear as absolutely straight lines, ideal circles, round holes, and other geometrically perfect features
- ✓ The actual surfaces of a manufactured part are determined by the processes used to make it
- ✓ The variety of manufacturing processes result in wide variations in surface characteristics

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Importance of Surfaces

- ✓ Smooth and scratch free surfaces more likely give a favorable impression to the customer
- ✓ Surfaces affect safety
- ✓ Friction and wear depend on surface characteristics
- ✓ Surfaces affect mechanical and physical properties
- ✓ Assembly of parts is affected by their surfaces
- ✓ Smooth surfaces make better electrical contacts

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Surface technology

Surface technology is concerned with

1) Defining the characteristics of a surface
2) Surface texture
3) Surface integrity
4) The relationship between manufacturing processes and the characteristics of the resulting surface

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Surface technology

- ✓ Characteristics of a surface:
  - ✓ Substrate: The bulk of the part that has a grain structure that depends on previous processing of the metal
  - ✓ Surface texture: Exterior of the part that is the surface has roughness, waviness, a pattern and/or direction resulting from mechanical process that produced it, and flaws
  - ✓ Altered layer: a layer below the surface of metal whose structure differs from that of the substrate
    - ✓ May result from work hardening (mechanical energy), heat treatment (thermal energy), chemical treatment, or even electrical energy

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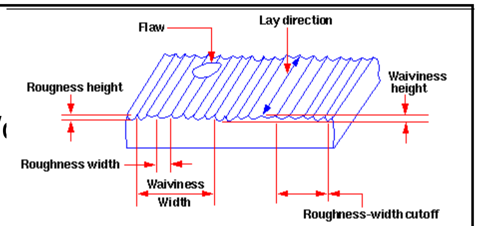
Surface texture



Surface characteristics (Courtesy, ANSI B46.1 - 1962)

- ✓ Consists of the repetitive and/ nominal surface of the object
- ✓ It is defined by four elements:
  - ✓ **Roughness:** refers to small, finely spaced deviations from the nominal surface that are determined by the material characteristics and the forming process
  - ✓ **Waviness:** is defined as the deviation of much larger spacing; they occur due to work deflection, vibration, heat treatment, and similar factors
  - ✓ **Lay:** the predominant direction or pattern of the surface texture and is determined by the manufacturing method
  - **Flaws:** are irregularities that occur occasionally on the surface

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Surface Finish Metrology

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- Why Measure Surface Finish?
- Measurement Methods
- Measurement Datums
- Reproducing The Surface
- Terminology
- Filters
- Parameters
- Surface Finish Standards
- Drawing Indication
- 3D (Areal) Measurement

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Applications of surface measurements

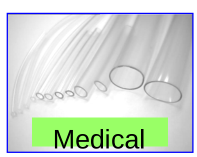
Bearing

Mixer Nozzle

Cans

Brake Disk

Ceramic Tile



Medical Tubes

Deodorant Ball

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Role of Surface Metrology

Manufacture ⟷ Function

Control | Prediction

Quality of Conformance ← SURFACES → Quality of Design

Variations in Value of Surface Parameter ← | → Absolute Value of Surface Parameter

- Process Control
- Improve Design
- Predict Behaviour

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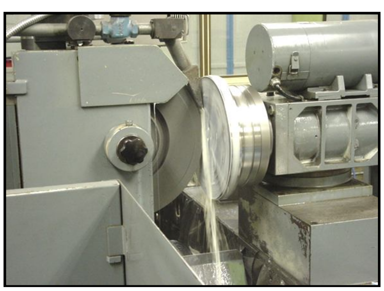
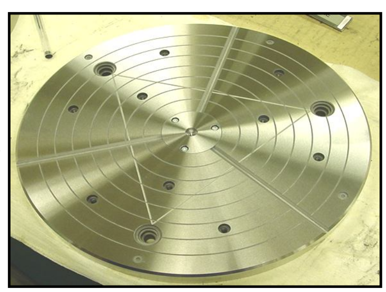
Role of Surface Metrology - Manufacture





The Ideal Situation

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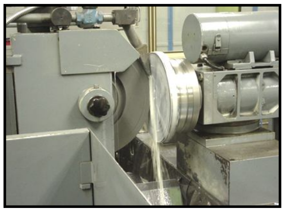
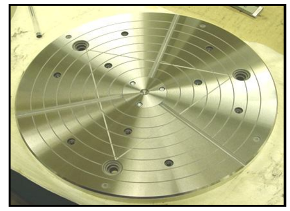
Role of Surface Metrology - Manufacture



The Reality:
Process Control



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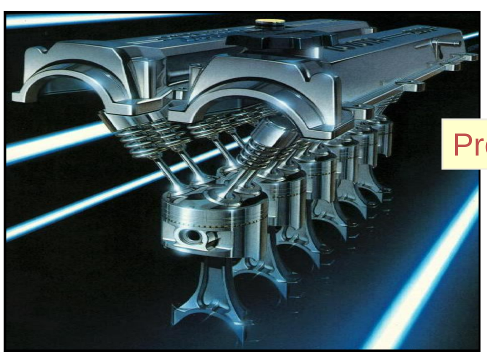
Role of Surface Metrology - Function



Predicting Component Behaviour

- ✓ To help optimise the function
- ✓ Future behaviour of the component can be predicted by taking a surface finish measurement

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Nature of Surfaces

- The microstructure of the material
- The action of the cutting tool
- The instability of the cutting tool on the material
- Errors in machine tool guideways
- Deformations due to stress patterns in the component

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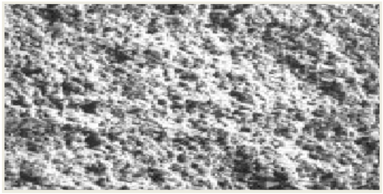
The Microstructure of the Material

Commercial Aluminium



White Paint

Blue Paint

Blue Plastic

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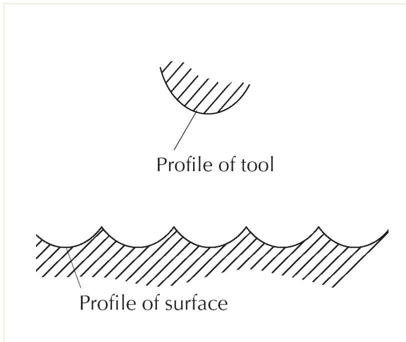
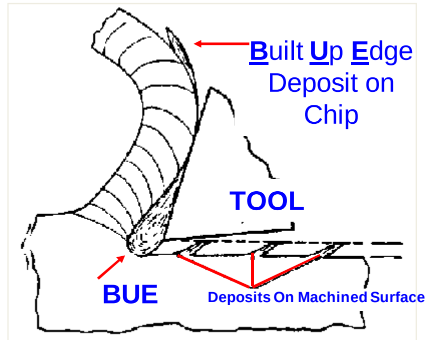
The Action of the Cutting Tool





Built Up Edge Degrades Surface Finish

- ✓ Surface Finish (roughness) is largely due to the reaction of the material and the cutting tool
- ✓ This is where variables like tool shape, speed, feed, Built Up Edge and the cutting fluid come into play.

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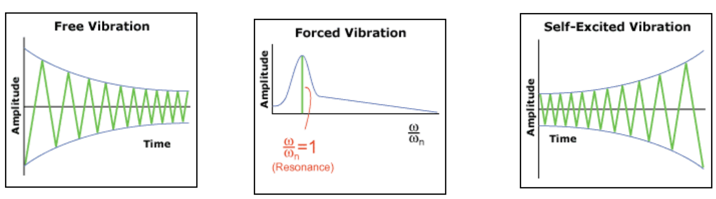
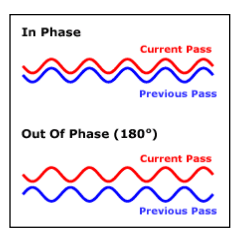
The Instability of The Cutting Tool



- ✓ Waviness is largely due to an imperfect or unstable machine tool. For example, imbalance in a grinding wheel
- ✓ Different types of vibrations that can occur during milling
- ✓ In milling operations, the magnitude of waviness is dependant upon the phase relationship of successive passes.

Milling



Regenerative Waviness.

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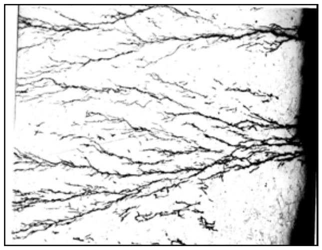
Stress Patterns In Components



Checks on raw material

Check during manufacturing process

Checks during product life.

Aircraft Crankshaft example

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Nature of Surfaces

- The microstructure of the material
- **The action of the cutting tool**
- **The instability of the cutting tool on the material**
- Errors in machine tool guideways
- Deformations due to stress patterns in the component

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Unwanted Properties on a Surface:

- Deep valleys which may be susceptible to crack propagation
- Too many peaks which may cause early surface breakdown and wear when in contact with a mating component
- Excessive waviness which may cause noise or indicate machining problems

Wanted Properties on a Surface:

- Sufficient valleys for oil retention when lubrication is an important factor
- Sufficient peaks for retention of paint and adhesives
- Sufficient distribution of valleys for formability
- Smooth surface profiles for reduced, noise, vibration or high reflectance

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Measurement Methods

- Initial Visual inspection
- Comparison Plates
- Contact Methods
- Non-Contact Methods

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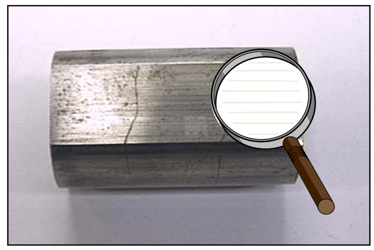
Initial Visual Inspection

- Hold Part Up To Light
- Use Eye-Glass if Required

Observe:

- Direction Of Lay
- Process Marks
- Defects / Scratches



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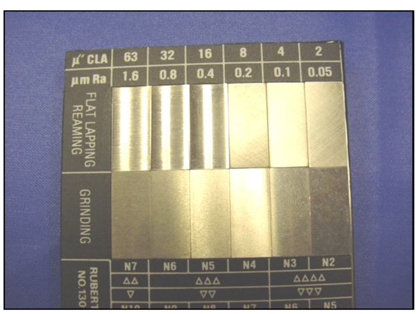
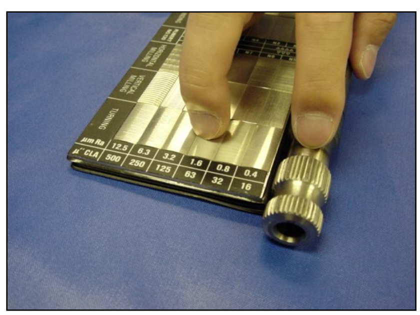
Comparison Plates





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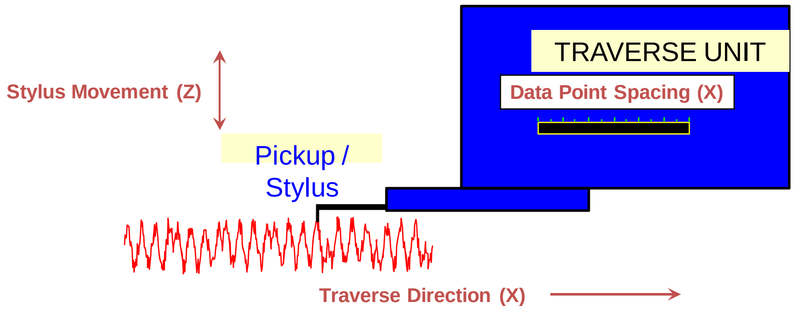
Contact Type Instruments



The contact type of instrument consists of a stylus which tracks across the surface under test. A gauge or pick-up which is a transducer that translates the movements of the stylus in the Z (height) direction as it tracks across the surface (X axis) into a usable electronic signal. This signal is then processed via software to present the operator with a value which represents the surface finish.

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Contact Type Instruments

The traverse mechanism will also provide X co-ordinate positions of the surface data by using a grating which has a fixed spacing. The Form Talysurf Series instrument has data point spacing in the X axis of 0.25μm (1μm for traverse lengths greater than 30mm).

Another method of data point collection is by utilising the motor driving the traverse unit. This method involves some form of positional feedback from the motor. Because the speed of the motor is known the position of the stylus can be determined at a set time period during the measurement, which dictates the data point spacing. This method, however, relies on the motor speed being constant to give accurate spacing between data points.

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Recent Contact Type Instrument

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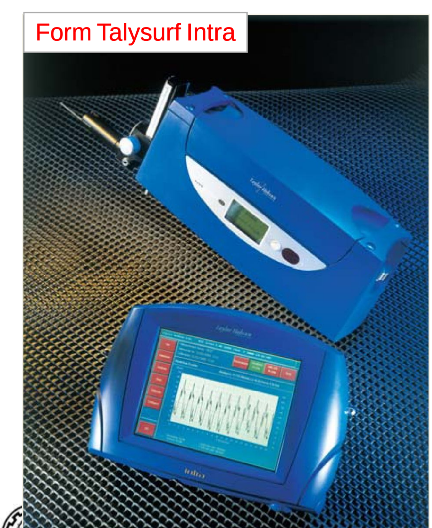
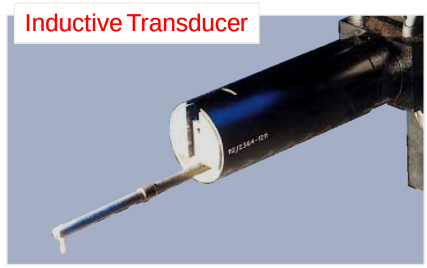
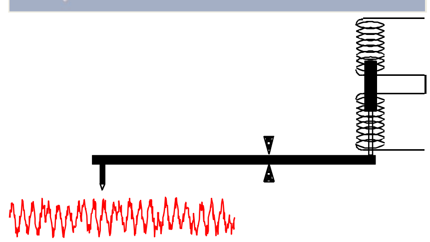
Instrument Using Inductive Transducer







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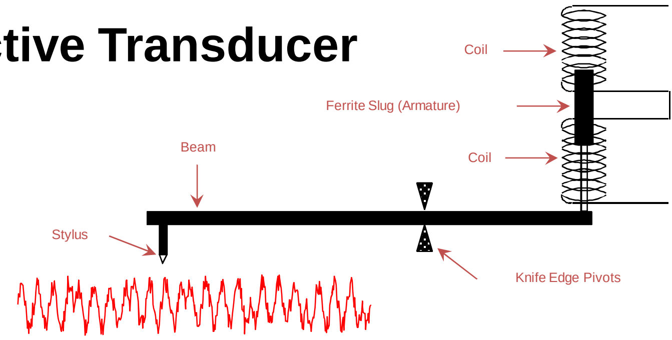
Inductive Transducer



- ✓ The stylus is located at one end of a beam
- ✓ The other end of the beam consists of a coil with a ferrite slug (armature) which moves inside two coils causing a change in relative inductance.
- ✓ As the stylus moves down a valley the ferrite slug will rise, when the stylus rides up a peak the slug will move down
- ✓ Two 10kHz signals in anti-phase are supplied to the transducer coil ends.
- ✓ The return signal, from the coil centre-tap, is demodulated to represent any stylus movement. (When the slug is in the central position, the return signal is zero.)

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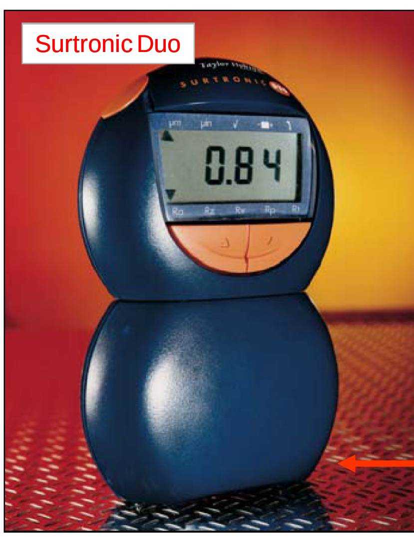
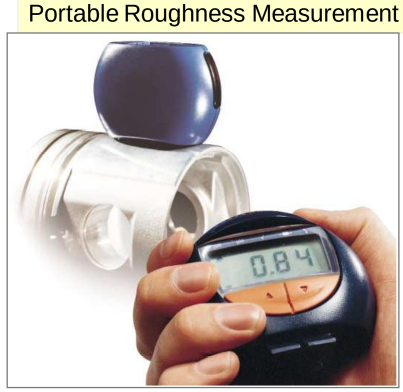
Instrument Using Piezo-Electric Transducer



Portable Roughness Measurement



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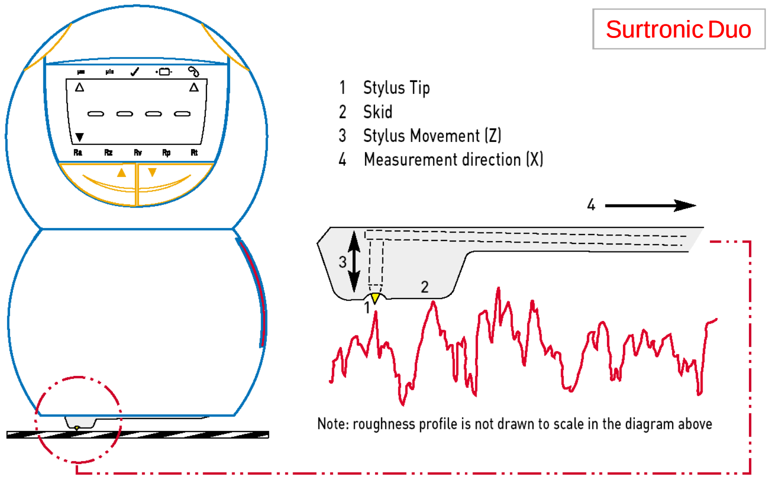
Instrument Using Piezo-Electric Transducer

Surtronic Duo



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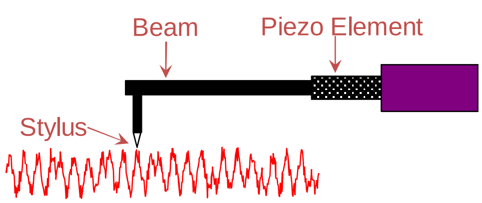
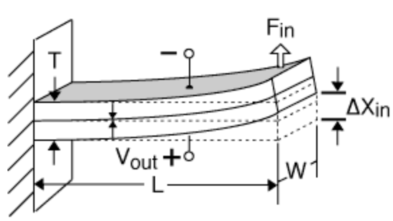
Piezo-Electric Transducer





Advantages

- Ideal For Small Portable Instruments
- Only Needs Simple Processing Electronics
- Ideal for Small Stylus Movements
- High Frequency Response

Disadvantages

- Small Range
- Low Linearity
- Temperature / Humidity Sensitive
- Limited Low frequency Response

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Interferometric Transducer - Laser

Measurement Methods

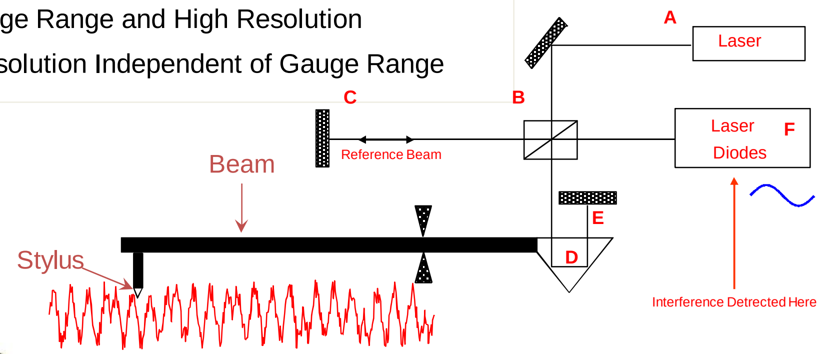
Advantages

Output is Related To Laser Wavelength

Extremely High Accuracy & Linearity

Large Range and High Resolution

Resolution Independent of Gauge Range



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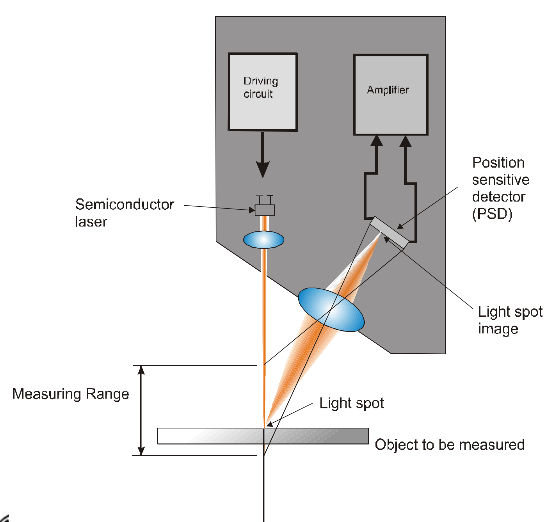
Non-Contact : Scattering Laser Triangulation



Advantages

High Speed 50,000pps

Slopes up to 90 deg

Low cost

Disadvantages

Spot size variation

Scattering only

Shadow areas

Limited Resolution

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Principle of Non-Contact : Scattering Laser Triangulation

✓ The laser emits a beam of light, which is reflected back of the sample surface at an angle, into a PSD detector receptor. The image is seen as a spot, the centre of which is calculated and its position on the PSD grating to give the altitude of the surface

✓ The main advantages of a non-contact type measurement system is the ability to measure fragile surfaces without causing damage. Measurements can be made at faster speeds using a non contact gauge and bi-directionally. This gauge is best suited for fast 3D measurement

✓ Disadvantages would include not being able to measure into small bores or traversing across widely changing shapes as easily as a standard contact stylus. The reflective properties of the surface will also dictate as to whether it is possible to be measured or not.

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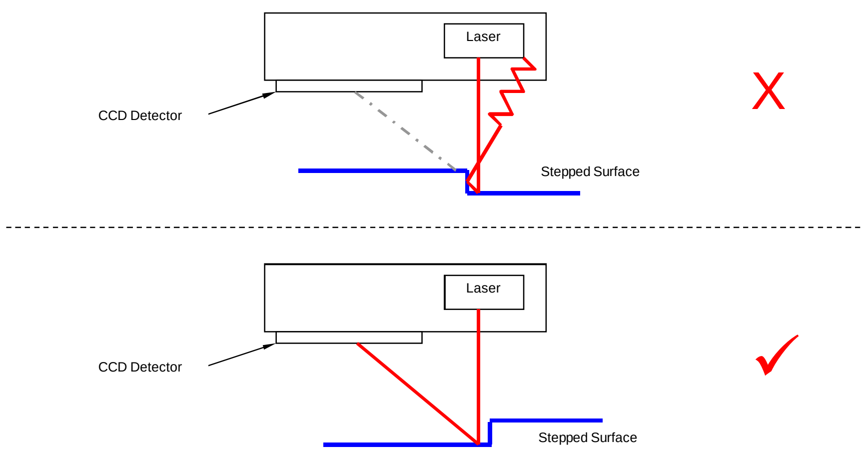
Non-Contact : Scattering Laser Triangulation



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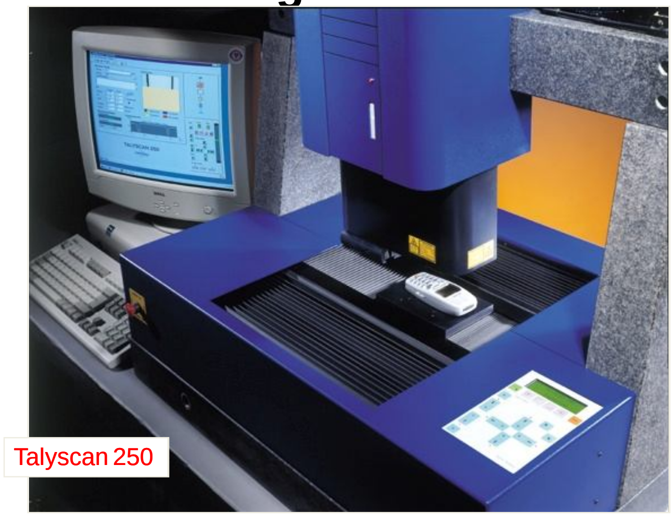
Instrument Using Scattering Laser Triangulation



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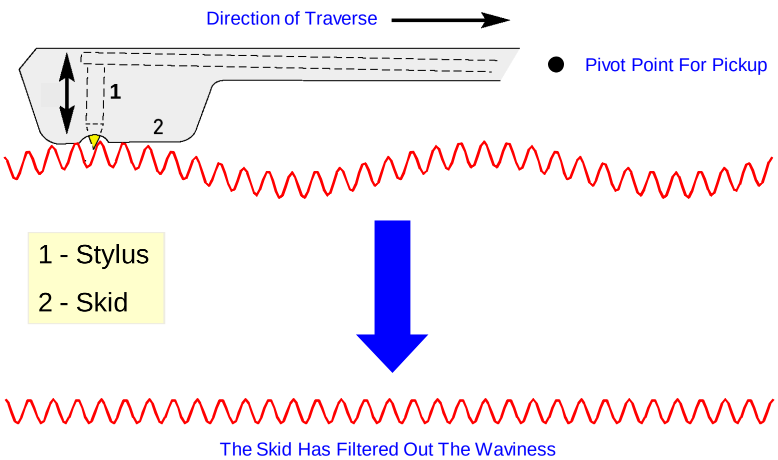
Skid (Surface) Datum



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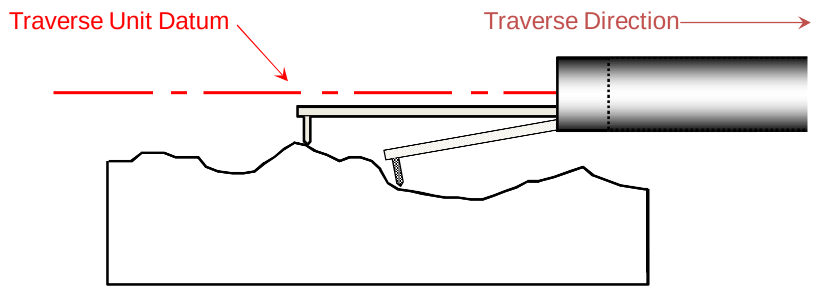
Independent Datums



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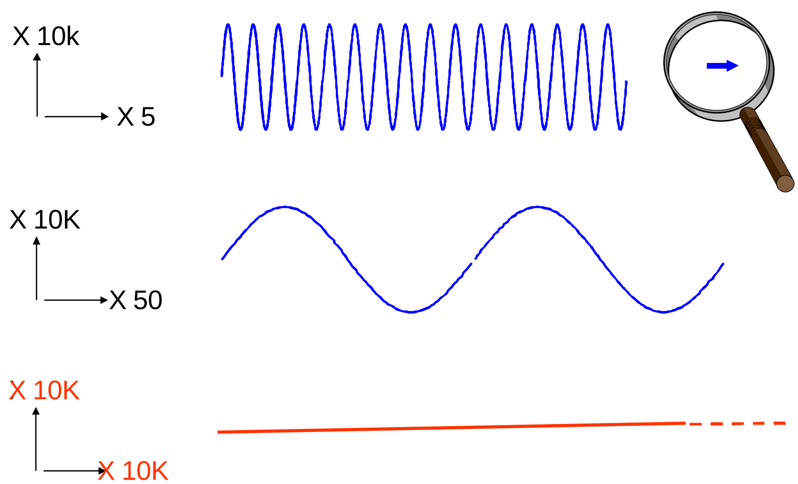
Interpreting The Graph - Scaling



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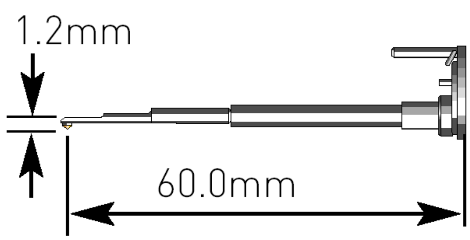
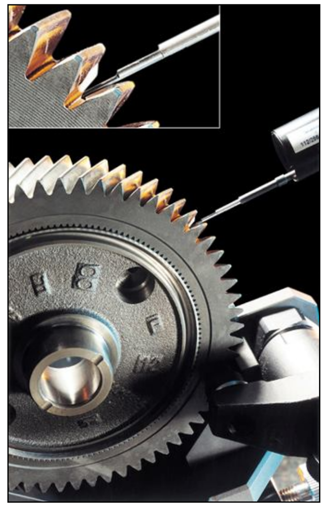
Stylus Types - Miniature Bore Stylus

Miniature Bore Stylus

2µm Conisphere Tip





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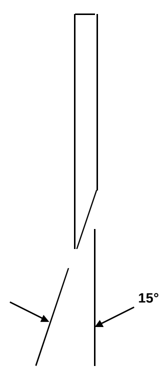
Stylus Types - Chisel Edge Stylus

Chisel Edge Stylus

20µm Tungsten Tip



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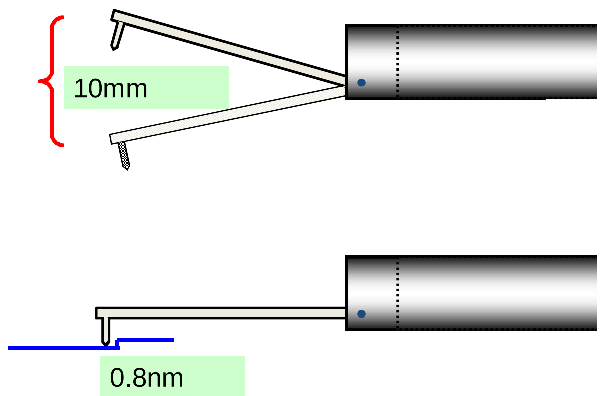
Gauge Range & Resolution

Gauge Range



Gauge Resolution:

Smallest stylus movement that can be 'detected'

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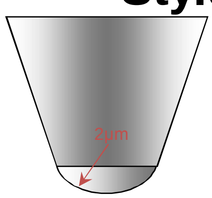
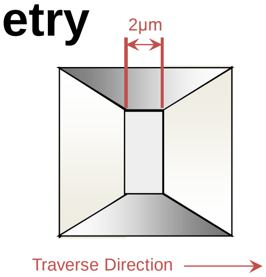
Stylus Tip Geometry



Conisphere Stylus



Truncated Pyramid Stylus

The 90° diamond tip conisphere and the 90° diamond tip, truncated pyramid. The truncated pyramid has a flat tip with a 2µm tip width in the traverse direction. This is designed in this way to give added strength to the stylus tip but this means that the tip is only useful in the single direction. The conisphere stylus, which has a spherical tip, can be used at 90° to the normal traverse direction whilst still having the correct stylus presentation to the surface. This is particularly useful for measuring difficult radii such as the fillet radii on crankshafts. The conisphere stylus can also have a 5µm tip and/or a 60° tip
Typical width of the truncated diamond tip is 7um.

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Filtering Effect of Stylus Tip

	Form	Waviness	Roughness
 Conisphere Tip r = 2μm	✓	✓	✓
 Ruby Ball Tip r = 500μm	✓	X	X

Refer to ISO 3274 For Details

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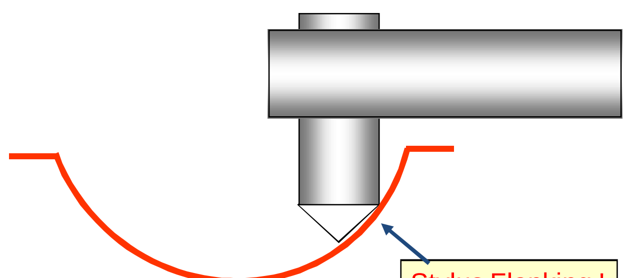
Stylus Flanking - On A Curved Profile



T = 1.15R for Diamond Tip Stylus T = 1.6R for Ball Stylus	T = Obtainable Traverse Length R = Profile Radius

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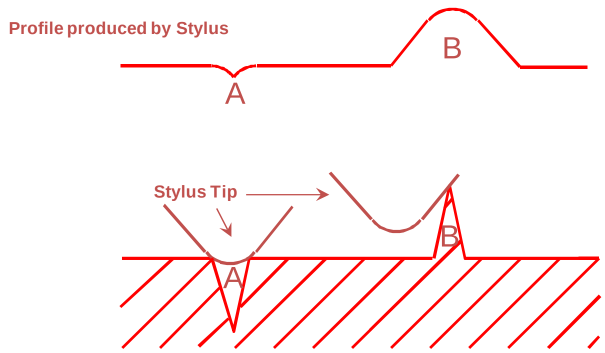
Reproducing the Surface - Limitations



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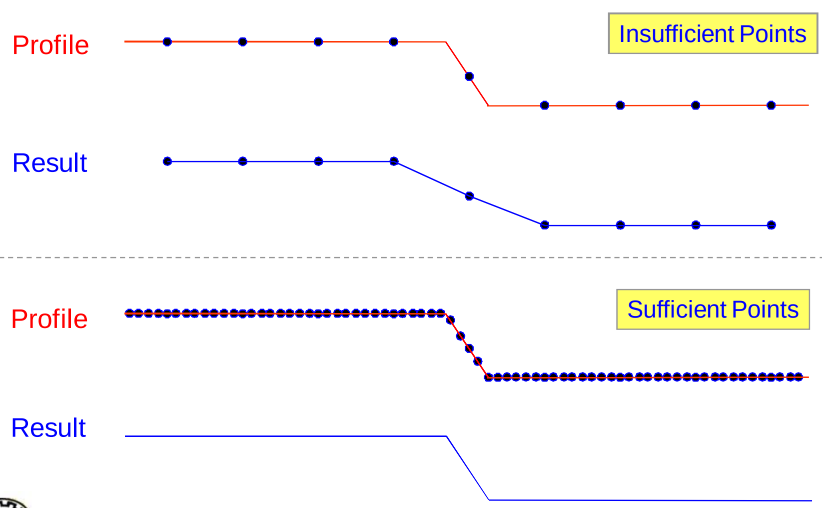
Data Points - Reproducing Slopes



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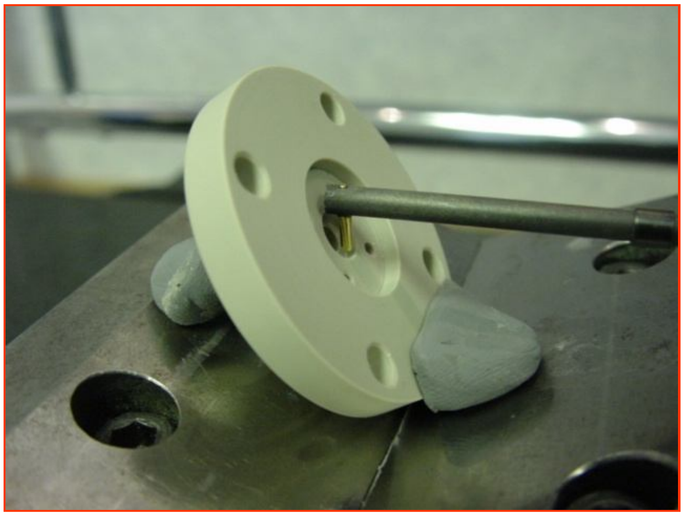
Tilting the Component



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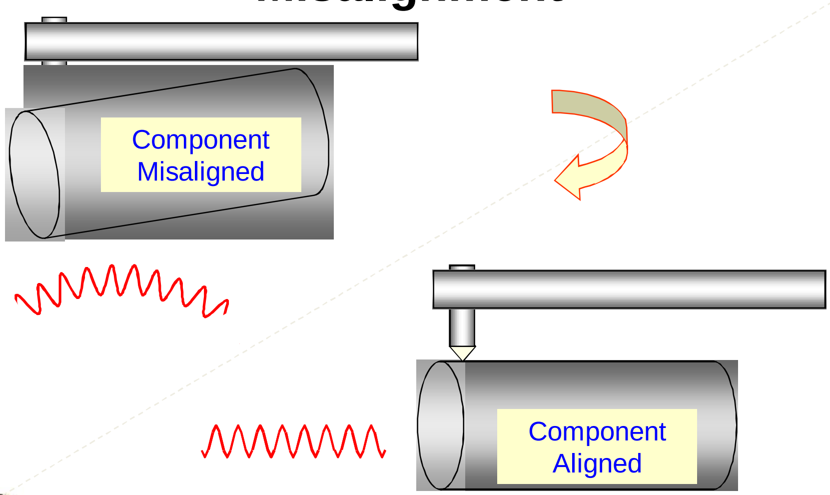
Form Error Due To Component Misalignment



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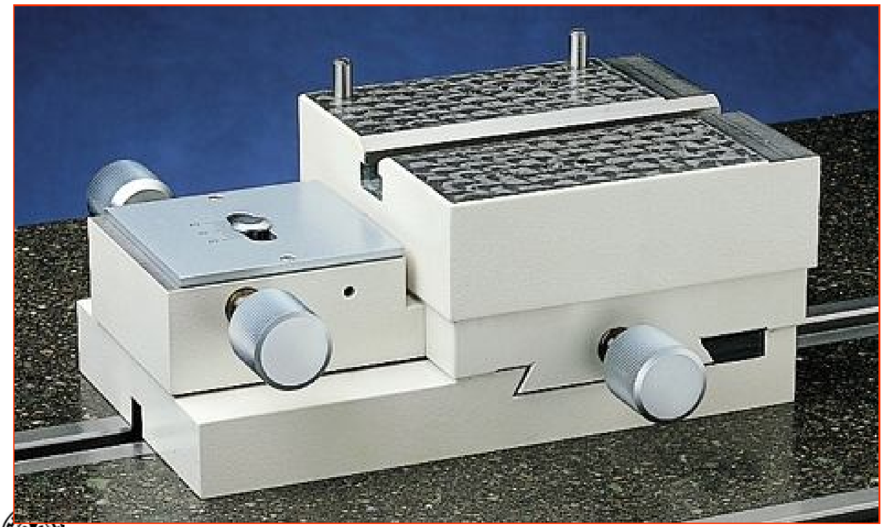
Fixture - For Component Alignment



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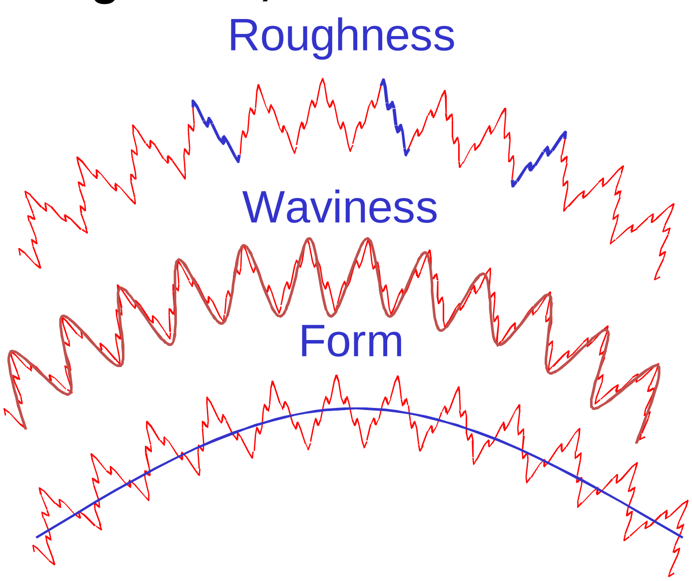
Roughness, Waviness & Form



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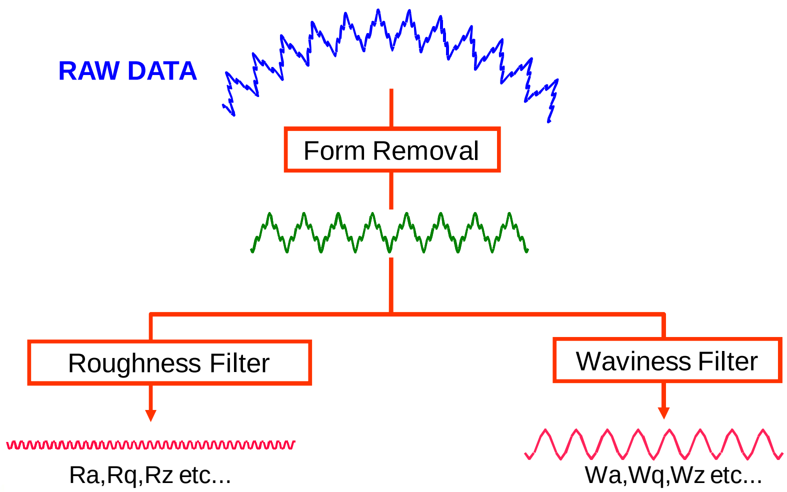
Filtering



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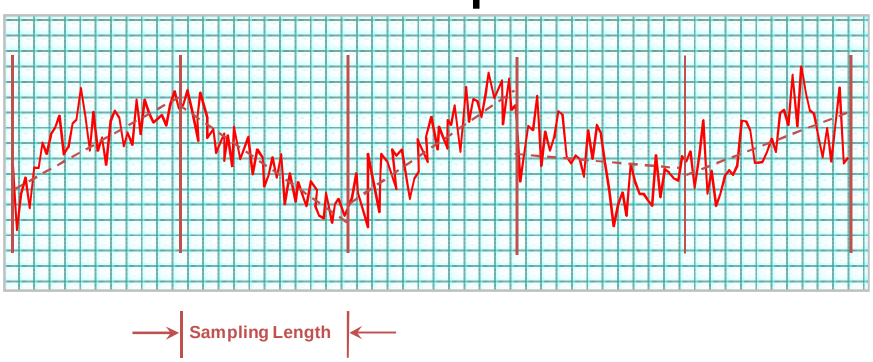
Filtering Using Graphical Techniques



For This Graphical Method, The Shorter The Sampling Length, The Greater The Attenuation Of Longer Wavelengths

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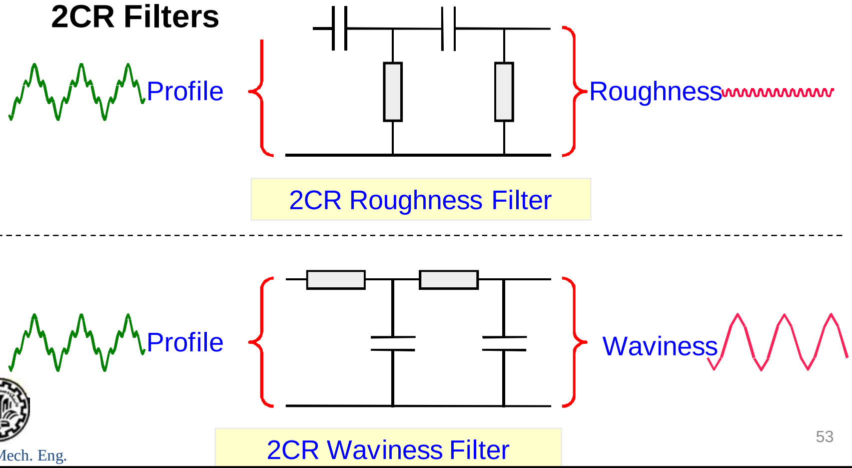
Filter Types

1. **ISO 2CR Filters;**
2. **2CR PC (Phase Corrected)**
3. **Gaussian Filter**

2CR Filters



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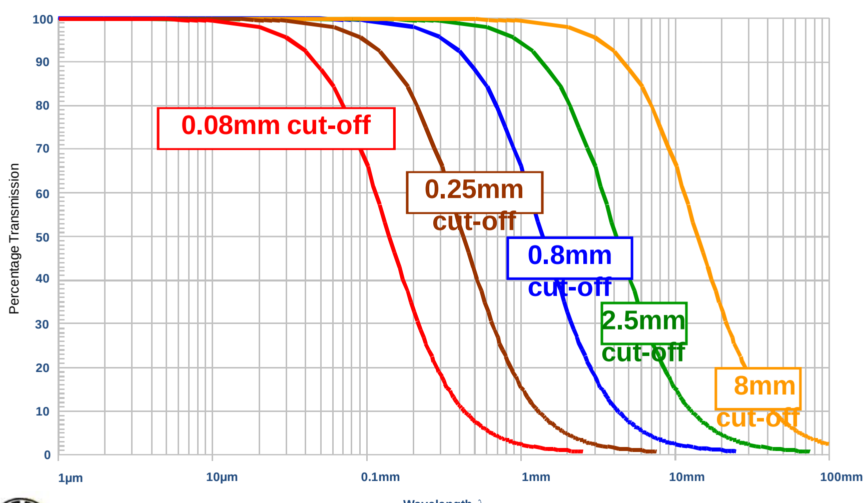
ISO 2CR Transmission Characteristic : Roughness



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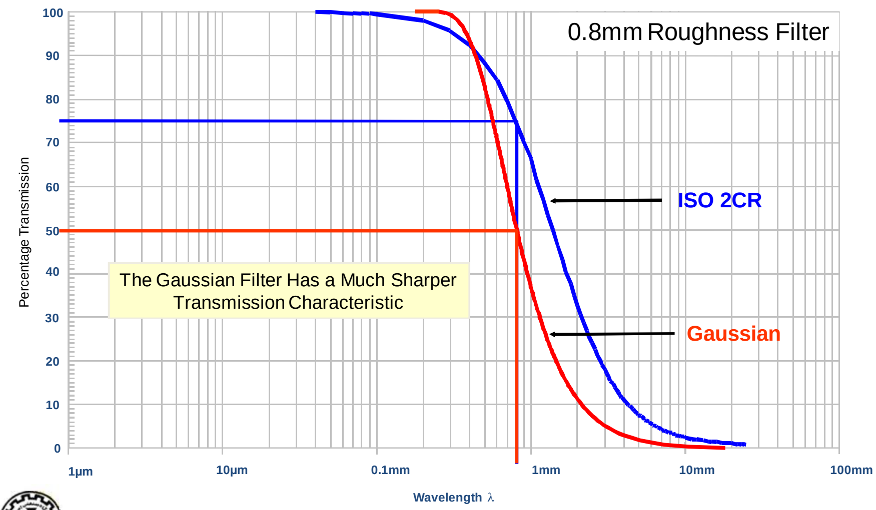
Gaussian vs ISO 2CR Response



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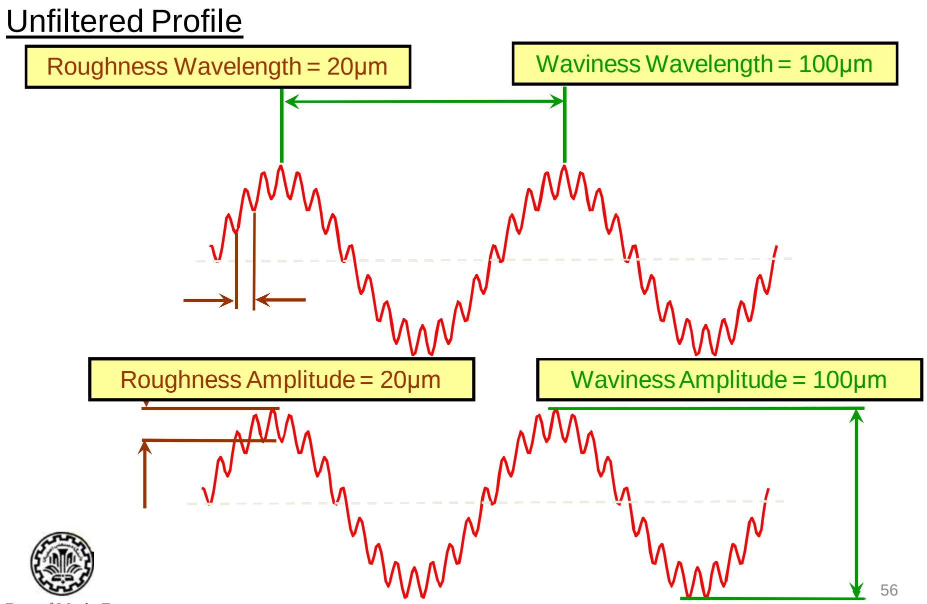
Example - Effect Of Roughness Filters



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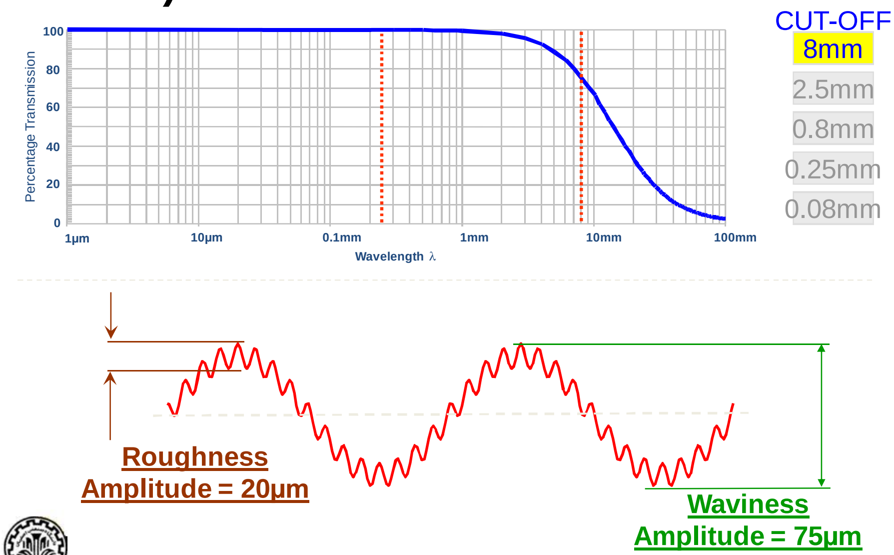
Example - Effect Of Roughness Filters (ISO 2CR)



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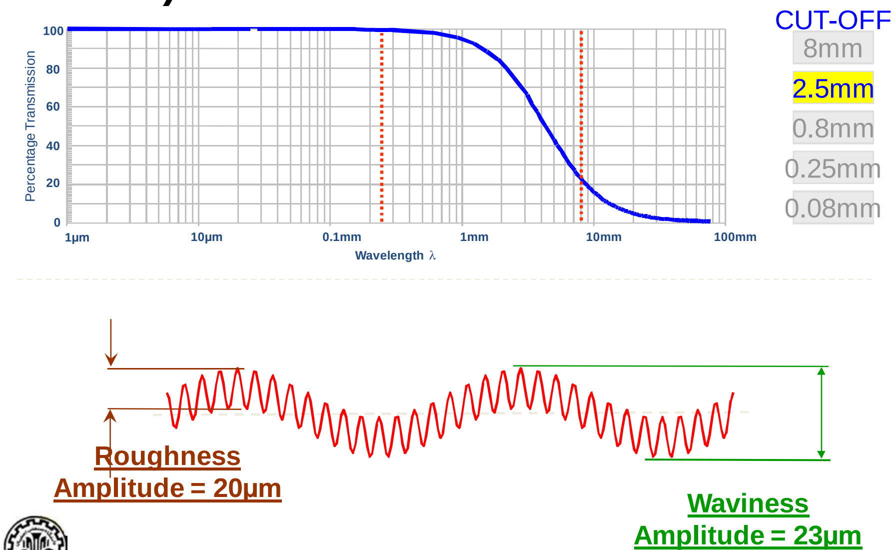
Example - Effect Of Roughness Filters (ISO 2CR)



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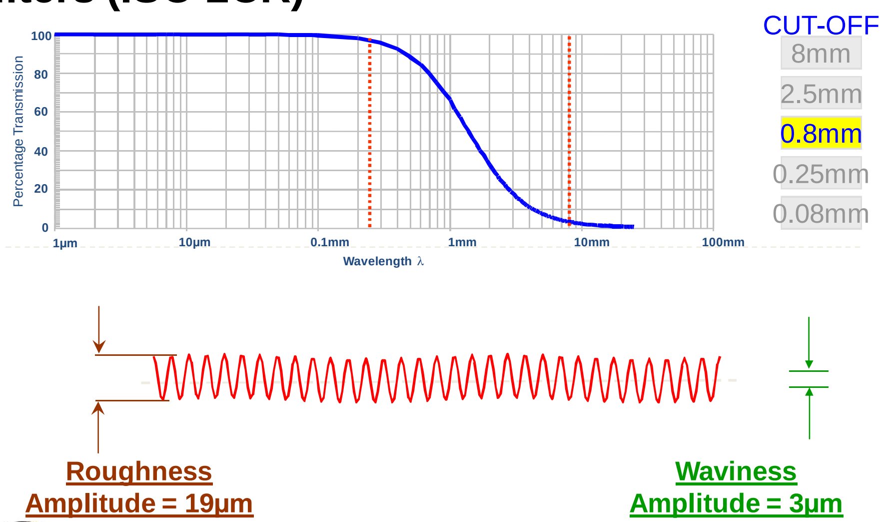
Example - Effect Of Roughness Filters (ISO 2CR)



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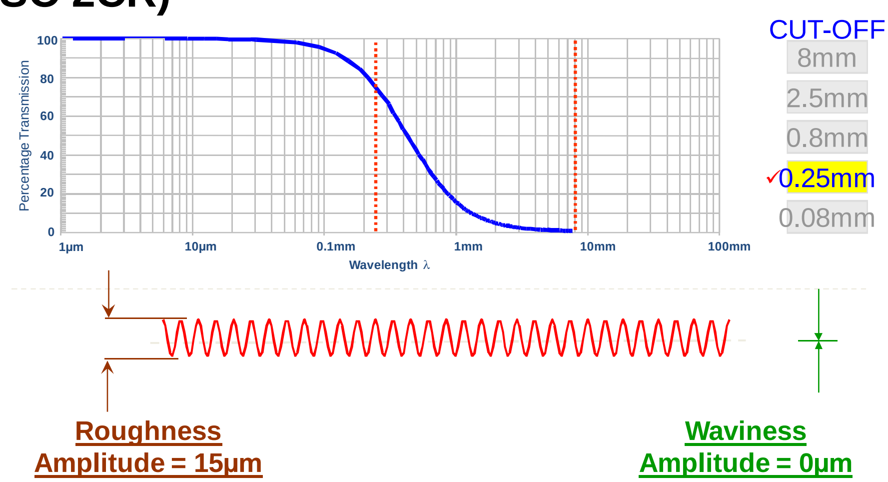
Example - Effect Of Roughness Filters (ISO 2CR)



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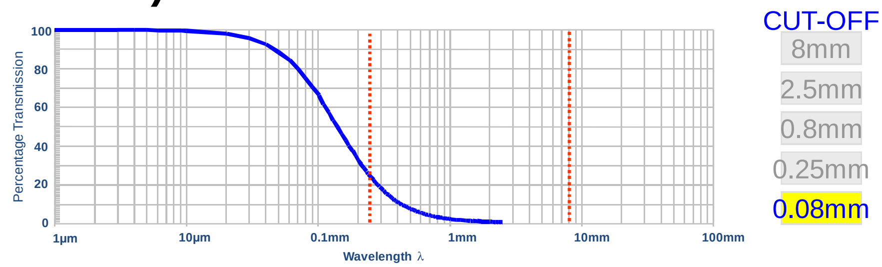
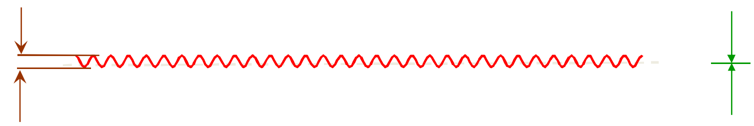
Example - Effect Of Roughness Filters (ISO 2CR)





Roughness Amplitude = 5µm

Waviness Amplitude = 0µm

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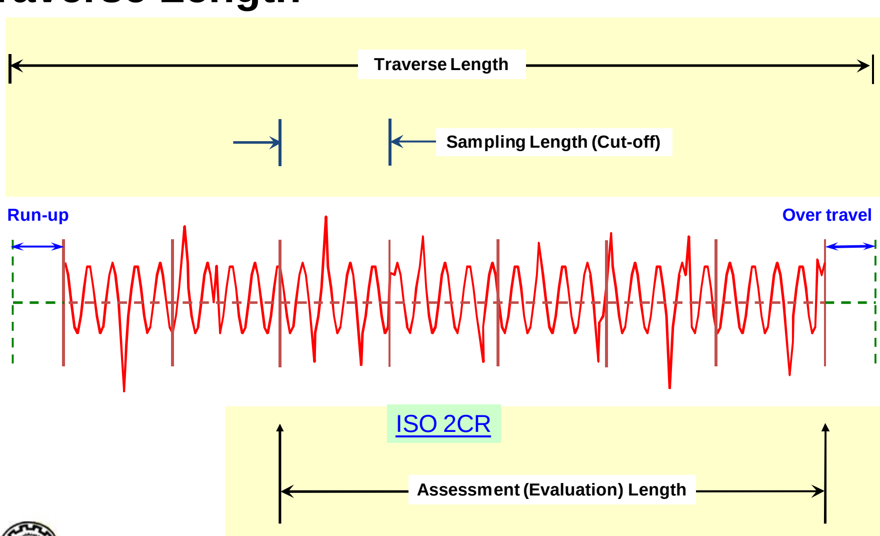
Sampling Length, Assessment Length, Traverse Length



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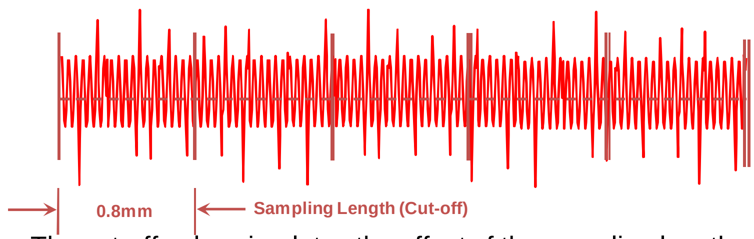
Choosing The Correct Filter (Cut-off) Value



- The cut-off value simulates the effect of the sampling length.
- The most common value cut-off used is 0.8mm, this value was obtained empirically by vast amounts of testing and evaluation.
- It was found that for most machined parts a sample length of 0.8mm would have around 20-30 crossings of the mean line.
- These crossings are created by the action of the cutting process, because of the amount of crossings a sample length of 0.8mm would be considered stable for statistical type analysis.

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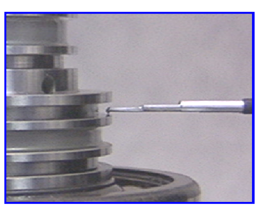
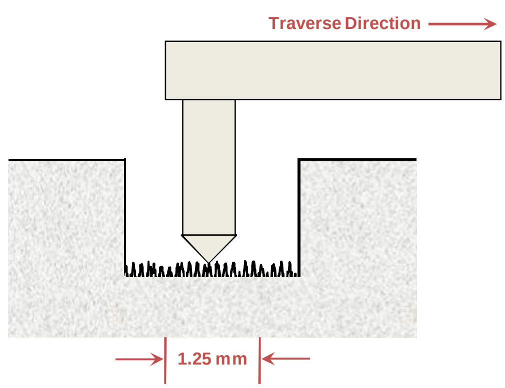
Choosing The Correct Filter (Cut-off) Value





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Choosing The Correct Filter (Cut-off) Value

Recommended Cut-off (ISO 4288-1996)

Periodic Profiles	Non-Periodic Profiles		Cut-off	Sampling Length / Evaluation Length
Spacing Distance RSm (mm)	Rz (μm)	Ra (μm)	λc (mm)	λc (mm) / L
>0.013-0.04	To 0.1	To 0.02	0.08	0.08 / 0.4
>0.04-0.13	>0.1-0.5	>0.02-0.1	0.25	0.25 / 1.25
>0.13-0.4	>0.5-10	>0.1-2	0.8	0.8 / 4
>0.4-1.3	>10-50	>2-10	2.5	2.5 / 12.5
>1.3-4.0	>50	>10	8	8 / 40

Unless otherwise indicated on a drawing, the table above should be used to determine the cut-off.

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Parameter Types

- Roughness : Prefix R
- Waviness : Prefix W
- Primary : Prefix P

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Parameter Types

- Amplitude Parameters defined from Z co-ordinates
- Spacing Parameters defined from X co-ordinates
- Hybrid Parameters defined from X & Z co-ordinates

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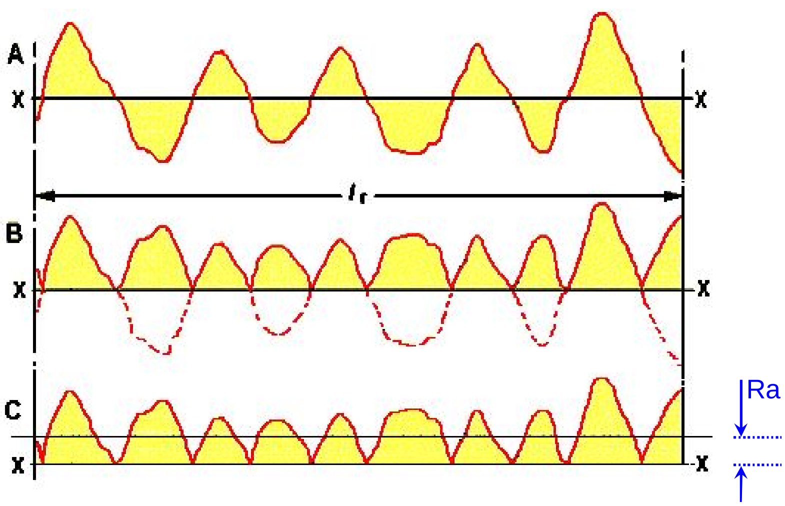
Average Roughness - Ra



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Average Roughness - Ra

- ✓ Ra is the most commonly used in surface finish measurement and has also been known in the past as Centre Line Average (CLA) or in the USA, Arithmetic Average (AA).
- ✓ Mathematically, Ra is the arithmetic average value of the profile departure from the mean line, within a sampling length.
- ✓ A method of visualising how Ra is derived is as follows:
  Graph A: A mean line X-X is fitted to the measurement data.
  Graph B: The portions of the profile within the sampling length "l" and below the mean line are then inverted and placed above the line.
  Graph C: Ra is the mean height of the profile above the original mean line.

- ✓ The Ra parameter is often misused. It should be noted that Ra is a controlling parameter, if the Ra value changes then the process it controls has changed, e.g.Cutting tip, speeds, feeds and cutting fluid (lubricant)

- ✓ Ra on its own does not tell us anything about the surface characteristics of the component under test.

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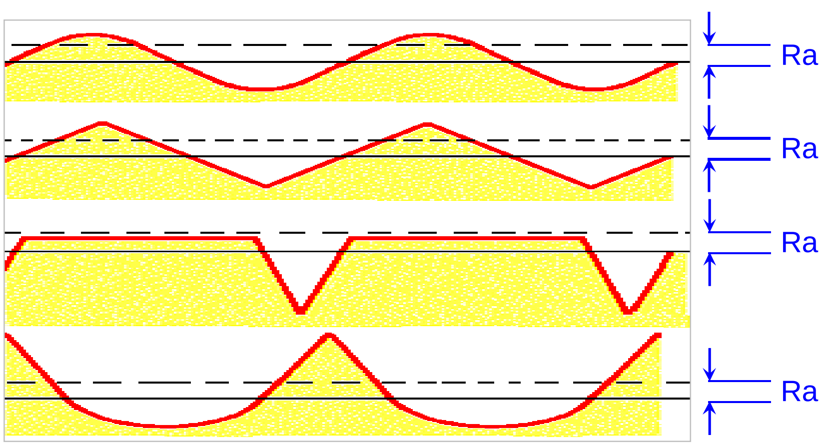
Ra Limitations



Same Ra - Different Surfaces

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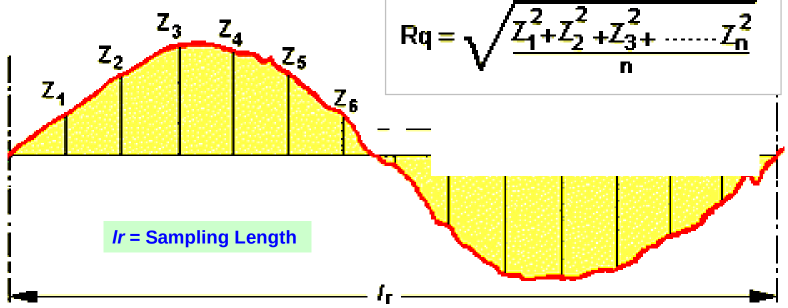
Root mean square - Rq (rms)

$$Rq = \sqrt{\frac{Z_1^2 + Z_2^2 + Z_3^2 + \cdots\cdots Z_n^2}{n}}$$



lr = Sampling Length

✓ Compared with the Ra parameter, Rq (rms) has the effect of giving extra weight to the higher values.

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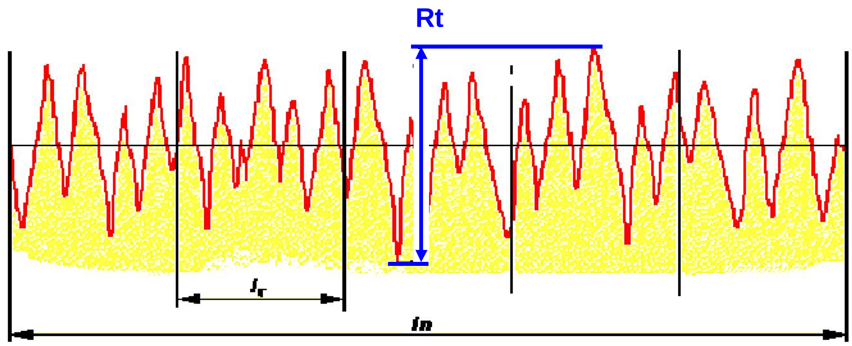
Maximum peak to valley - Rt



lr = Sampling Length

ln = Assessment Length

This parameter is particularly useful where components are subjected to high stresses, any large peak to valley could be areas which are likely to suffer from crack propagation, however because this is a peak parameter it is subject to large variations and can be unstable.

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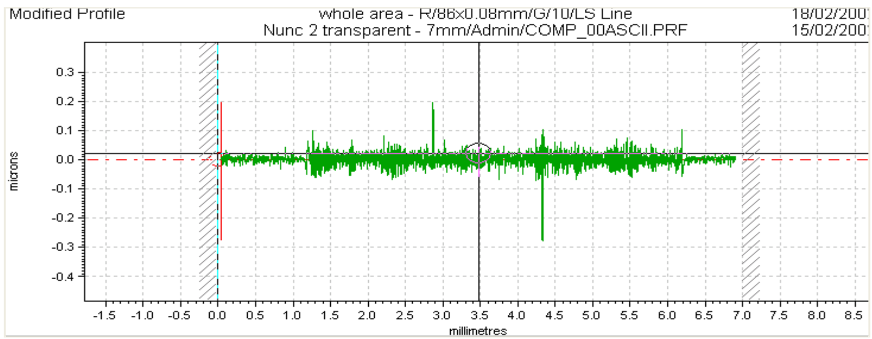
Rt Results are Divergent



Note: A single scratch or peak can affect Rt

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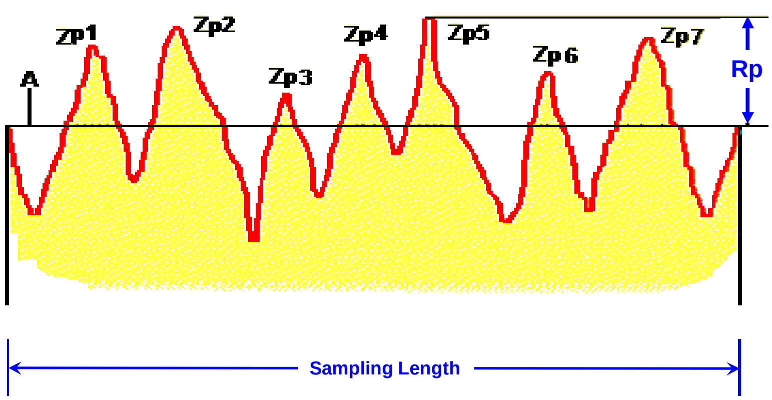
Maximum height above the mean line - Rp



Peaks are important when considering friction and wear properties, as the interaction between surfaces concentrates around them. The presence of peaks can make dimensional measurements on components that are subjected to wear unreliable, as wear removes the peaks that were originally included in the measurement.

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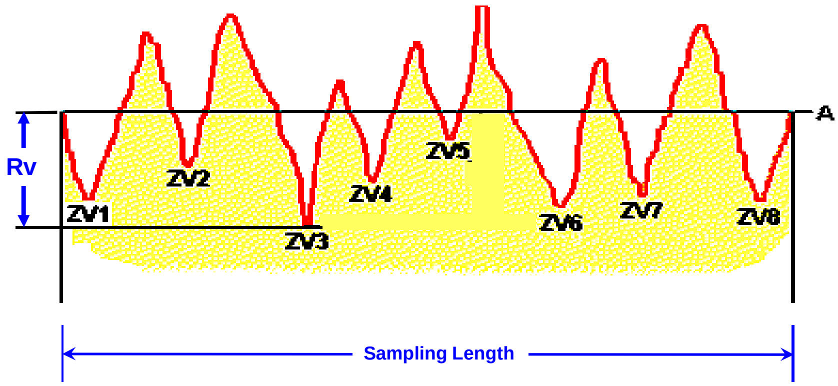
Maximum depth below the mean line - Rv



Valleys are important for the retention of lubrication. However, fracture propagation and corrosion start in valleys.

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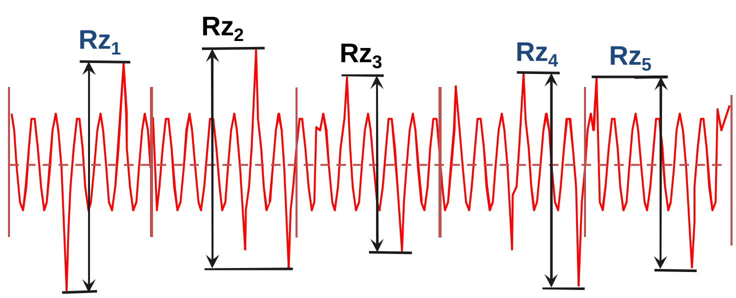
Rz



$$Rz = (Rz_1 + Rz_2 + Rz_3 + Rz_4 + Rz_5 . . .) / n$$

n = number of sampling lengths

The Rz parameter definition as shown here is the mean of all the Rt values taken from each sample length.

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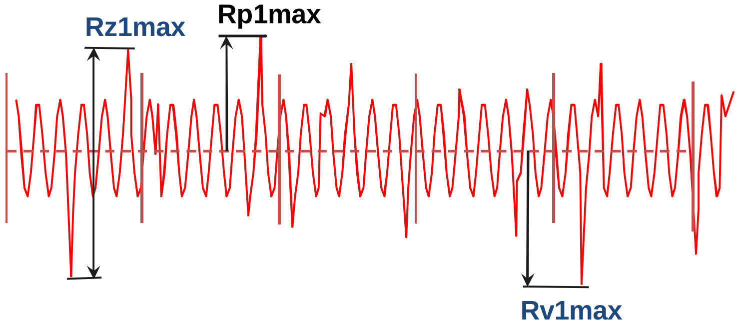
Rz1max, Rp1max, Rv1max



The Rz1max parameter is defined as the largest of the individual peak to valleys from each sample length

Rp1max parameter is the largest of the individual peak to mean line from each sample length

Rv1max parameter is defined as the largest of the individual mean line to valleys from each sample length

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[redacted]

Indication	Maximum Permissible Value Rt (μm)				Meaning
	Row 1	Row 2	Row 3	Row 4	
No Sign	Free	Free	Free	Free	No specific Demands on the Surface
~	Free	Free	Free	Free	Demands Concerning Consistency and Look
▽	160	100	63	25	surfaces with a roughness which must not exceed the maximum permissible Rt Value
▽▽	40	25	16	10	
▽▽▽	16	6.3	4	2.5	
▽▽▽▽	-	1	1	0.4	

- Triangle Symbols are still used on many drawings.
- This method is no longer valid & was cancelled in 1978.
- It has been superseded by ISO 1301

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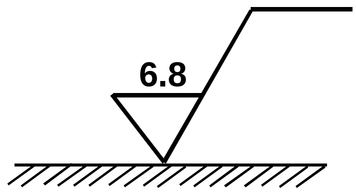
Graphical Symbols For Surface Texture



Conventional Surface Texture Symbol

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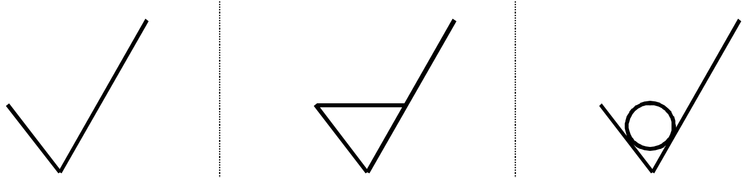
Graphical Symbols For Surface Texture

1 | 2 | 3



1. Requirement for Surface Texture
2. Requirement for Surface Texture, Material Removal Required
3. Requirement for Surface Texture, Material Removal Not Permitted

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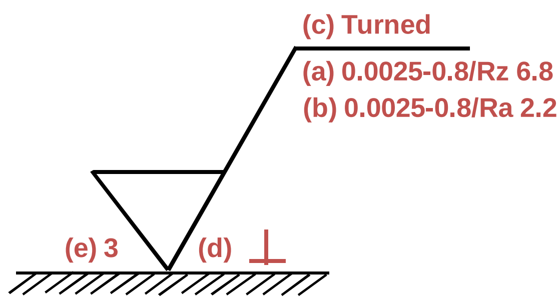
Graphical Symbols For Surface Texture



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Drawing Indication of Surface Lay

TYPE	LAY	SYMBOL
Parallel		=
Perpendicular		⊥
Crossed		X
Multi-directional		M
Particulate		P
Circular		C
Radial		R

See ISO 1302

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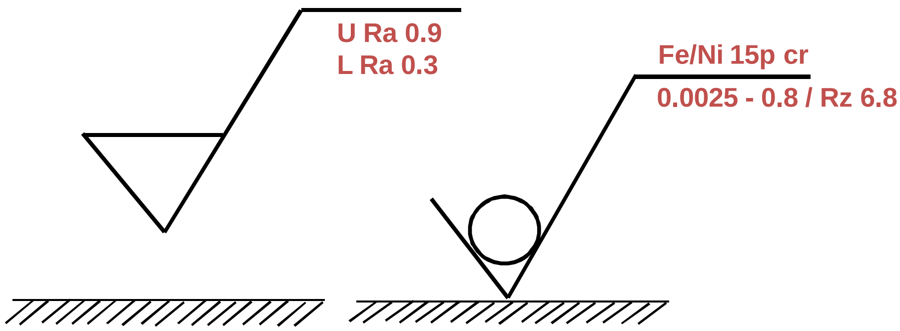
Graphical Symbols For Surface Texture



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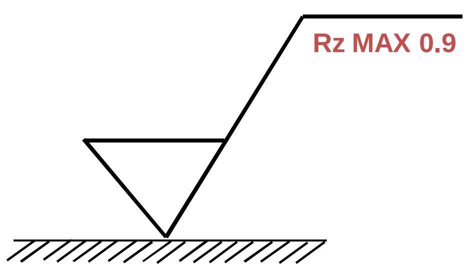
The MAX Rule



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Surface finish standards

TERMINOLOGY

ISO 4287:1997	Geometrical Product Specifications (GPS) – surface texture: profile method – terms, definitions and surface texture parameters ....
ISO 6813:1985	Measurement of roundness – terms, definitions and parameters of roundness ....
ISO 8785:1998	Geometrical Product Specification (GPS) – surface imperfections – terms, definitions and parameters

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Surface Finish Standards

ISO 3274:1996	Geometrical Product Specifications (GPS) – surface texture: profile method – nominal characteristics of contact (stylus) instruments ....
ISO 4288:1996	Geometrical Product Specifications (GPS) – surface texture: profile method – rules and procedures for the assessment of surface texture ....
ISO 4291:1985	Method for the assessment of departure from roundness – measurement of variations in radius
ISO 4292:1985	Methods for the assessment of departure from roundness – measurement by two- and three-point methods ....
ISO 5436:1985	Calibration specimens – stylus instuments – types, m calibration and use of specimens ....
ISO 11562:1996	Geometrical Product Specifications (GPS) – surface texture: profile method – metrological characteristics of phase correct filters...
ISO 12085:1996	Geometrical Product Specification (GPS) – surface texture: profile method – motif parameters.......................
ISO 13565–1:1996	Geometrical Product Specification (GPS) – surface texture: profile method: surfaces having stratified functional properties – Part 1: filtering and general measurement conditions ....
ISO 13565–2:1996	Geometrical Product Specification (GPS) – surface texture: profile method: surfaces having stratified functional properties – Part 2: height characterization using the linear material ratio curve ....

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Ra - Applications

- Ra is a controlling parameter, if the Ra value changes then the process it controls has changed, e.g.Cutting tip, speeds, feeds and cutting fluid (lubricant).
- Ra is the most commonly used parameter in industry and is available in the simplest and lowest priced instruments from all manufacturers.
- The averaging nature of Ra makes it a stable parameter which is not influenced by odd or spurious spikes or scratches.
- For extremely fine surfaces Ra is not sensitive enough to pick out the odd or infrequent defects that are important - See Rq
- The Primary version Pa is often used on very short surface such as ‘O’ ring grooves where filtering would remove relevant detail affecting the performance of the seal.
- The Waviness version Wa can predict the performance of larger scale sealing faces as those on gaskets such as cylinder heads. There is not enough compliance in the components structure to flatten out large waviness features and thus the seal may fail.

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Rq (rms) - Applications

- Rq has the effect of magnifying single or odd spikes and valleys, thus making it a parameter which differentiates between very smooth surfaces with similar surface with non typical marks or defects.
- For statistical work, Rq values are more meaningful than arithmetic averages ones. This parameter is not used very much in general engineering, but is used more in the optical and electronic substrates industry due to it’s ability to detect spurious peaks and valleys.
- High Rq values on mirrors or lens surfaces will signal potential image quality reduction and or local distortions.
- The Primary version Pq is used to assess the quality of seal in ‘O’ Ring Grooves and the interaction between the rubber and metal surfaces.Such short length surfaces do not require the normal roughness filters as they would remove relevant detail.

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Rt - Applications

- Rt is the maximum peak to valley height of the profile in the evaluation length (ln), however because this is a peak parameter it is subject to large variations and can be unstable.It shows the extreme limits of the profile - but they may not be co-incident.
- Rt is used as a controlling parameter, particularly useful where components are subjected to high stresses, any large peak to valley could suffer from crack propagation.
- Singular large peaks can also penetrate oil lubrication films increasing wear , debris and damage to sliding surfaces.
- Electrical contact effectiveness and the risk of arcing or sparking from singular non typical peaks.
- The Primary version Pt is used to quantify the overall Form Error of a component or surface.

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Rp and Rv - Applications

- Rp is the maximum height of the profile above the mean line within a sampling length divided by n sampling lengths.
- Peaks are important when considering friction and wear properties, as the interaction between surfaces concentrates around them. The presence of peaks can make dimensional measurements on components that are subjected to wear unreliable, as wear removes the peaks that were originally included in the dimensional measurement.
- Rv is the maximum depth of the profile below the mean line within a sampling length or averaged over ‘n’ sampling lengths.
- The Rv parameter is useful where stress is a functional criteria. Deep valleys can be surface cracks and not simply deep machining marks.
- Valleys are important for the retention of lubrication. However, fracture propagation and material corrosion start in valleys.

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Rz - Applications

- This parameter has similar uses to the Rt parameter but is a little more stable as it has averaging involved when assessed over a number of Sampling Lengths.
- Rz is an alternative to Rt as a controlling parameter.
- Oil film penetration probability in sliding contact bearings.
- Electrical contact effectiveness and likelihood of arcing or burning.

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Rz1max - Applications

- Rz1max is a controlling parameter, particularly useful where components are subjected to high stresses, any large peak to valley could suffer from crack propagation.
- Singular large peaks can also penetrate oil lubrication films increasing wear , debris and damage to sliding surfaces.
- Rz1max is an alternative to Rt as a controlling parameter in that it is a local max height.
- Oil film penetration probability in sliding contact bearings.
- Electrical contact effectiveness and likelihood of arcing or burning.

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Rp1max - Applications

- Peaks are important when considering friction and wear properties, as the interaction between surfaces concentrates around them. The presence of peaks can make dimensional measurements on components that are subjected to wear unreliable, as wear removes the peaks that were originally included in the dimensional measurement.
- Singular large peaks can also penetrate oil lubrication films increasing wear , debris and damage to sliding surfaces.
- Rp1max is an alternative to Rt as a controlling parameter in that it is a local max height and is only concerned about material above the mean line.
- Oil film penetration probability in sliding contact bearings.
- Electrical contact effectiveness and likelihood of arcing or burning.

Rv1max - Applications

- The Rv1max parameter is useful where stress is a functional criteria. Deep valleys can be surface cracks and not simply deep machining marks.
- Although controlled valleys are important for the retention of lubrication, fracture propagation and material corrosion also start in valleys.
- Where Rv varies from the Rv1max parameter it is an indication the surface valley features are varying along the profile length. Such randomness in the surface is better catered for by combining peak parameters with averaging parameters.

[redacted]

Cutting with Single or Multiple Tool Tips	Turning, Milling, Broaching, Planing ...
Abrasive Machining	Grinding, Polishing, Honing ...
Physical & Chemical Machining	Electrochemical Machining, Elecrodischarge Machining ...
Other Machining	Laser Machining, High-Power Water Jet ...
Ultra-fine Machining (nanomachining)	Ion Beam Milling, Energy Beam Machining ...
Forming, Casting, Extrusion	

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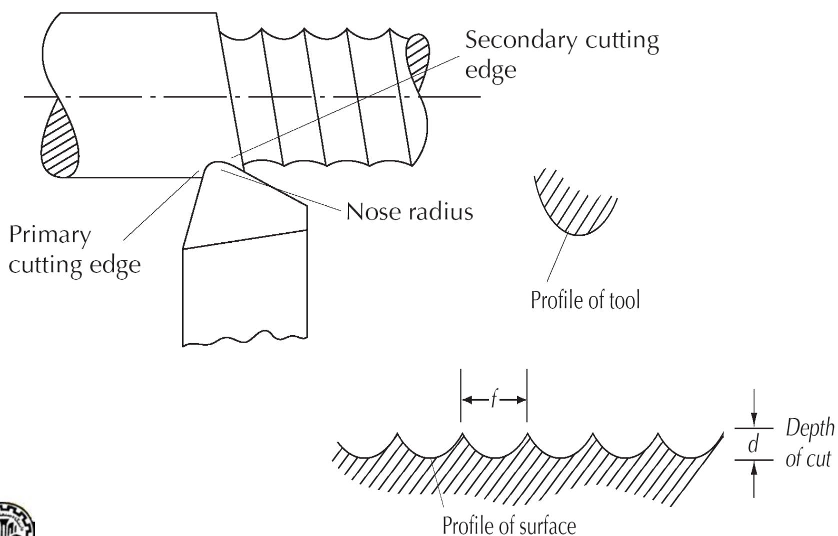
Cutting Tool - Primary & Secondary Cutting Edges



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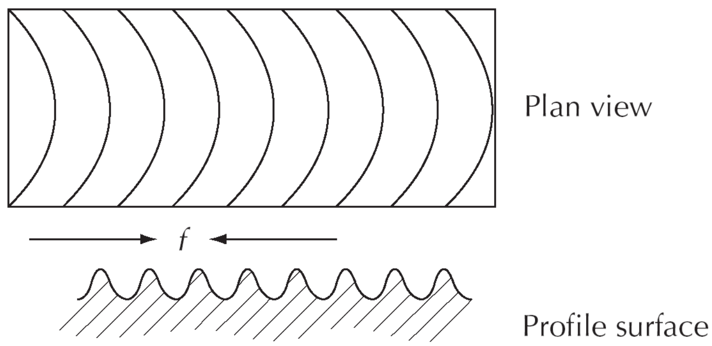
Surface Appearance of Face Milling Single Tooth



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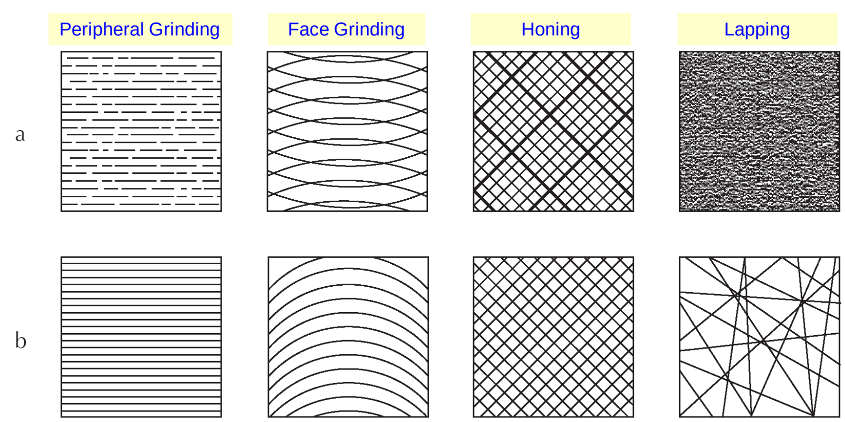
Abrasive Processes



(a) and (b) are process variations.

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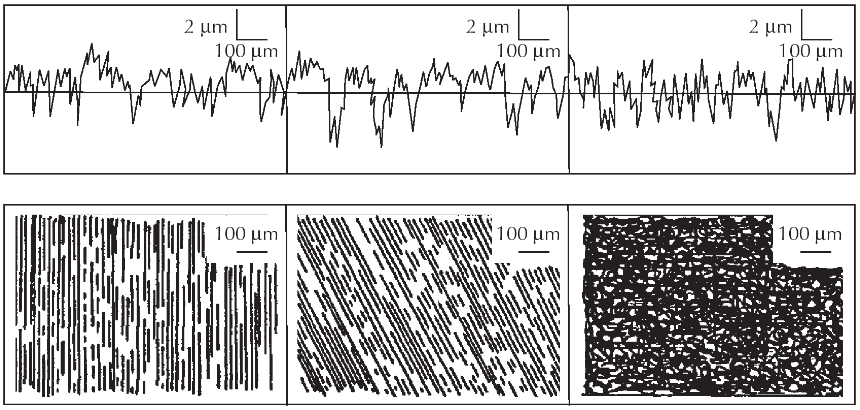
Different Abrasive Processes - Same Rz



Grinding | Honing | Lapping

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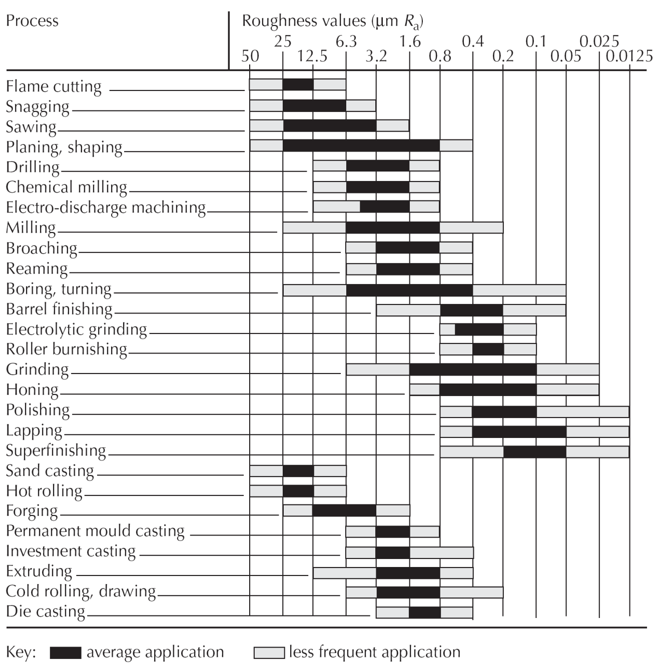
Typical Ra Values Produced By Common Processes



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