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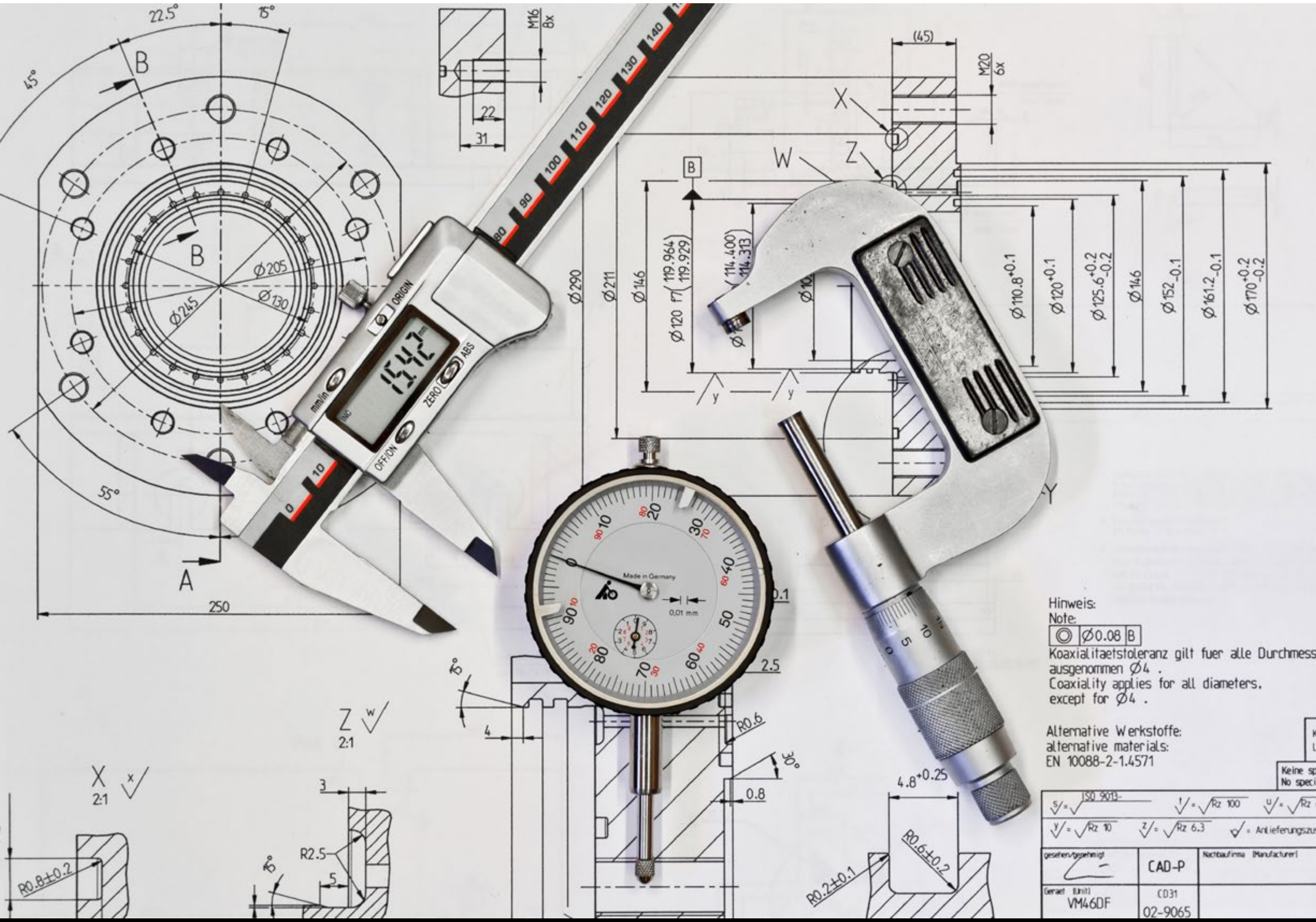

The Basics of Dimensional Measurement and Measuring Instruments

Measurement Fundamentals

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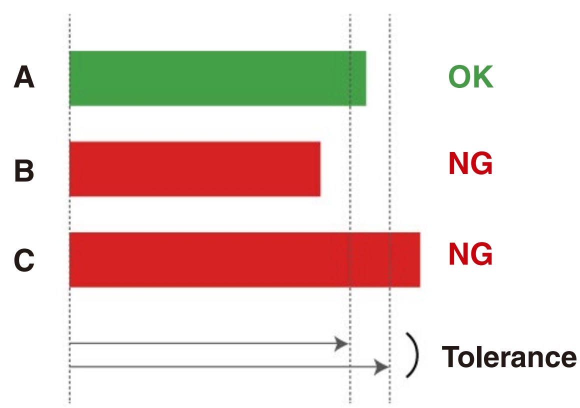
Measurement System Basics

Correct measurements are a key factor in manufacturing. Without a good understanding of the requirements and rules, errors may occur as a result of incorrect measurement. This section introduces the basics of measurement systems.

What is Measurement?

In this document, “measurement” refers to the numeric expression of a manufactured object’s dimensions based on a fixed reference (unit). Simply explained, dimensional measurement is the comparison of the measurement target against a reference object. The reference object is the measuring instrument, and there is a wide variety of measuring instruments that offer different measurement purposes, methods, and accuracy levels. It is possible to “inspect” whether a manufactured object fits the required specifications (tolerance) by correctly measuring the object’s dimensions. In other words, performing thorough measurements is one of the basic rules of better manufacturing.



! Correct measurement is a basic rule of inspection

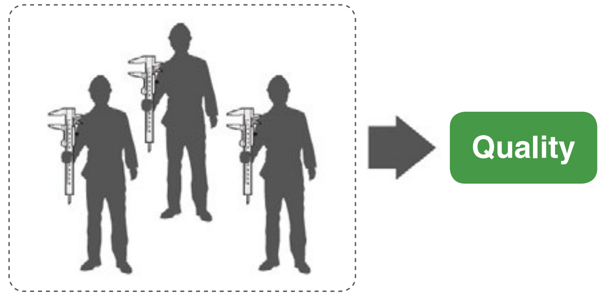
Measurement System Basics

The Importance of Measurement in Manufacturing

It goes without saying that correct dimensional measurement is a key factor in manufacturing. Performing measurements with the same reference throughout all processes—from material reception to processing, assembly, inspection, and shipping—makes it possible to create products that match the design exactly and to guarantee product quality.

If even one person performs inaccurate measurements, product quality can be compromised. Should this lead to defective products being mixed in with good products, the result will be a worse yield. In addition, shipping defective products as finished products will lead to complaints from customers. In other words, it is essential that all members of an organization perform correct measurements throughout every step of the manufacturing process.

The basic principle for correct measurements is to ensure that all those involved in manufacturing are skilled in measuring, and that the measuring instruments are correctly managed and used. These basics make up an initiative known as “Measurement Control”, which is a core concept of quality control. In recent years, measurement control has been standardized as measurement management systems (ISO 10012). Also, initiatives for metrological traceability have been proceeding steadily in order to guarantee correct measurements.



Correct measurements performed by all workers

Direct and Indirect Measurements

There are two methods for performing dimensional measurements: direct measurement and indirect measurement.
With direct measurements, measuring instruments such as Vernier calipers, micrometers, and coordinate measuring machines are used to measure the dimensions of the target directly. These measurements are also known as absolute measurements. Measurements can be performed over a wide range specified by the scale of the measuring instrument, but there is also the chance that the measurement will be wrong due to erroneous readings of the scale.
With indirect measurements, the dimensions are measured using measuring instruments such as dial gauges that look at the difference between targets and reference devices such as gauge blocks and ring gauges. The more predetermined that the shape and dimensions of a reference device are, the easier the measurement becomes. However, this method also has the disadvantage of the measurement range being limited.

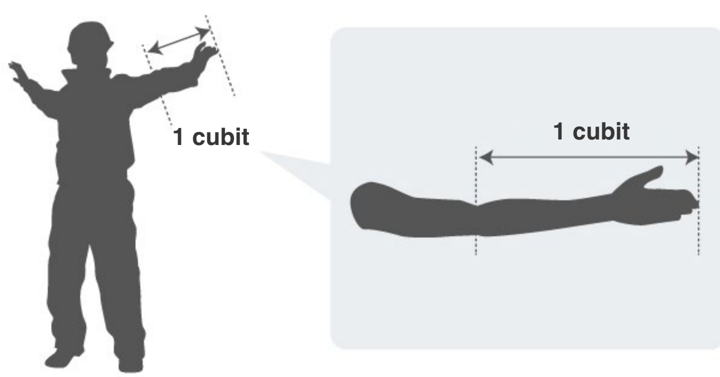
Units

History of Length Units

Using the Human Body as the Reference

The way base units of length have been determined has changed greatly over time. Long ago, the base for reference was the human body. For example, the cubit was a unit that indicated the length from the elbow to the fingertips. This unit was used in ancient cultures in Mesopotamia, Egypt, and Rome. The length varied from region to region, ranging from 450 to 500 mm 17.72" to 19.69". Studies have proven that the pyramids of Egypt, known for their accurate construction, were built using two types of cubits: a long one and a short one. It is said that the standard measure of length in these eras was the body of the country’s ruler or some other powerful individual. Even today, units of length based on the human body are used in countries such as the United States, such as the yard, foot, and inch.

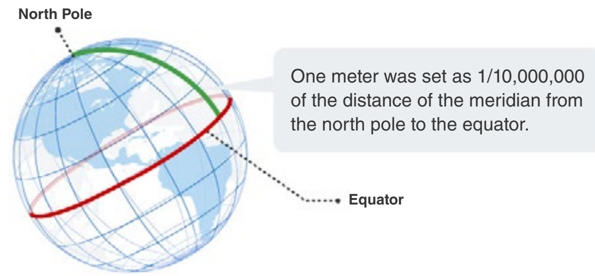
Using the human body as the unit of length



Measurement System Basics

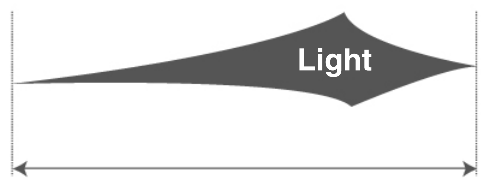
Using the Earth as the Reference

Length units based on the human body were used for thousands of years. This continued until a major change took place around 200 years ago. As the Age of Discovery came to an end and industry grew primarily in Western Europe, it became necessary to unify units of length on a global scale. In the 17th century, discussions were held in Europe regarding the unification of units. After a century of discussions, France proposed the unit of the meter (meaning “to measure” in Greek) in 1791. The reference at this time was the distance of the meridian from the north pole to the equator. One meter was set as 1/10,000,000 of this distance. Later, a prototype meter using an alloy of platinum and iridium, which is highly resistant to oxidation and abrasion, was created in France at the end of the 19th century as a result of the need to unify dimension references on a global scale.



Using the Speed of Light as the Reference

From the onset, a unit that uses the Earth as the reference was understood to be difficult to apply for measurement. Problems also arose regarding errors during the creation of and the deterioration over time of the prototype meter. This led to discussions regarding the creation of a new reference. During the General Conference on Weights and Measures (CGPM) held in 1960, the length of one meter was defined according to the wavelength of orange light emitted from the element krypton-86 in a vacuum. In 1983, thanks to advances in laser technology, the length of one meter was defined on the basis of the speed of light and time. Today, one meter is defined as “the distance that light travels in a vacuum in 1/299,792,458 of a second”, as defined in 1983.



Distance traveled in 1/299,792,458 of a second = 1 m

International System of Units

For weights and measures such as length, the same measurement should, in principle, have the same unit anywhere in the world.
To that purpose, the International System of Units was defined during the General Conference on Weights and Measures (CGPM) in 1960.
The abbreviation “SI” comes from the name of this system in French, Le Système International d’Unités.
In the International System of Units, the meter (m) is used as the SI unit (base unit) of length. SI prefixes are written in front of the unit.
For example, “km” includes the prefix k (kilo; 10 to the power of 3) followed by m.

SI base unit

Material	Name	Symbol
Length	Meter	m

SI prefixes (symbols that indicate integral multiplications of 10)

Symbol	Symbol	Exponential representation	Value to multiply the unit by
Mega	M	1×10^{6}	1,000,000
Kilo	k	1×10^{3}	1,000
-	-	1×10^{0}	1
Centi	c	1×10^{-2}	0.01
Milli	m	1×10^{-3}	0.001

Errors

Types of Errors

Errors in length are differences between the target's true value and the measured value, or between the reference value and the measured value. They are expressed as "error = measured value - true value". In actuality, it is difficult to obtain the true value no matter how precise the measurement is, so it is unavoidable that some uncertainty will exist in the measured value.
Errors can be classified into three major types according to the factor that generates the error. Such factors must be carefully considered to prevent errors.

Systematic errors

With this type of error, the measured value is biased due to a specific cause. Examples include measurement variations resulting from differences between individual instruments (instrumental errors), temperature, and specific ways of measuring.

Random errors

This type of error is caused by random circumstances during the measurement process.

Negligent errors

This type of error is caused by the inexperience of or the incorrect operations performed by the measuring individual.

Causes of Errors

The following are the major causes of errors that may occur during measurement.

Errors caused by temperature

An object's volume changes due to fluctuations in temperature, which also leads to changes in the object's length. This applies not only to the measurement target but also to the measuring instrument. Changes in temperature and the length of an object can be expressed by the "thermal expansion coefficient". The thermal expansion coefficient varies depending on the material type. ISO defines the reference temperature for measuring length as 20°C 68°F.

Major thermal expansion coefficients

Unit: $\times 10^{-6}$/K

Diamond	1.0
Glass	8 to 10
Iron	11.8
Gold	14.2
Aluminum	23.1
PET plastic	70.0

Formula for amount of deformation due to thermal expansion:
ΔL = L (Length of material) × α (Thermal expansion coefficient) × ΔT (Temperature difference)
Note:
Values are based on a temperature condition of 293 K (20°C 68°F).

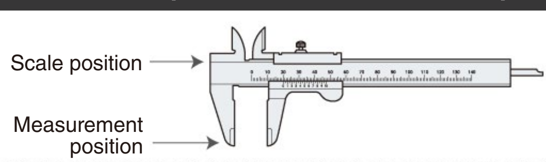
Errors caused by material deformation

Applying force to an object causes it to change at a fixed ratio. The object will return to its previous state when the force is no longer applied. This change in the object's shape is called "Elastic deformation". The force applied to the object is called "stress". In general, the relationship with the strain of the object is proportional. Therefore, this relationship can be expressed with the "Modulus of longitudinal elasticity (Young's modulus)". The stronger the stress, the greater the strain. For example, care must be taken to avoid tightening the spindle too much when using an outside micrometer to measure the outside of an object.

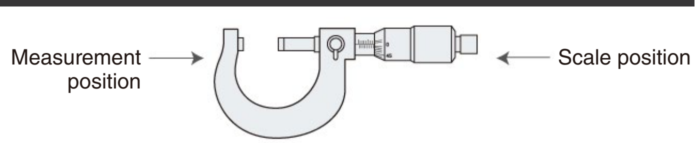
Abbe's Principle

Abbe's principle relates to accuracy when measuring dimensions. The principle is also an important guideline for designing measuring instruments. This principle states that, "In order to improve measurement accuracy, the measurement target and the scale of the measuring instrument must be placed in a collinear fashion in the measurement direction".
When applied to actual measuring instruments, the principle implies that while the scale and the measurement position are collinear for outside micrometers, the scale and the measurement position are at a distance from each other for hand calipers. In other words, outside micrometers follow Abbe's principle, while hand calipers do not. Therefore, it can be said that outside micrometers have a higher measurement accuracy.

Hand calipers do not follow Abbe's principle



Micrometers follow Abbe's principle



Tolerance and Fit

What is Tolerance?

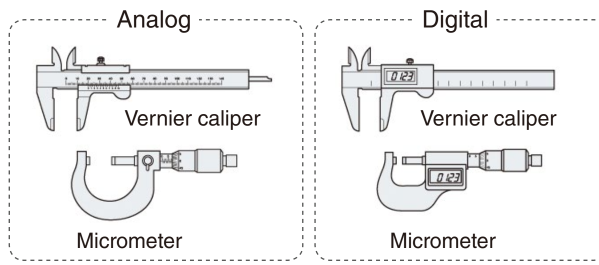
A certain amount of error will inevitably occur between the measured value and the true value. What is important is to specify the allowable range of errors. In terms of measurement, the difference between the maximum and minimum dimensions of permissible errors is called the “tolerance”. The allowable range of errors prescribed by law, such as with industrial standards, can also be referred to as tolerance.
If “60 (+0.045 -0.000)” is written on a drawing, “60” represents the reference dimension, and “+0.045 -0.000” indicates the tolerance of the upper and lower limits. In this case, the upper limit is 60.045 and the lower limit is 60.000.
One of the reasons for establishing tolerances for practical applications is to find a balance between the processing cost and the intended functions of the object. Increases in accuracy lead to corresponding increases in processing costs. The important point is to ensure that the required functions and quality are achieved, and tolerances must be set accordingly.

What is Fit?

One reason to set a tolerance is that the dimensional difference must be determined when engaging multiple parts, such as a shaft being engaged to a bore. This is called fit, or clearance.
When considering the fit, the way to approach measurement differs depending on whether to base measurement on the shaft or the hole. For example, when considering the diameter of the shaft as the basis, if the shaft only needs to go through the bore, a clearance fit can be used. If the shaft needs to be fixed to the bore, it must be an interference fit. For something in between, a location/transition fit is used.

Analog vs. Digital

In recent years, the digitization of measuring instruments has steadily progressed. For example, finding a hand caliper or micrometer with a digital counter is no longer rare. Whereas practice was once required to accurately read the Vernier scale on a pair of hand calipers, digital hand calipers instantaneously display measurements in units as small as 1/100.
However, digital measuring instruments do not provide advantages only. With digital instruments, the display may change frequently due to the adjustment of the applied force during measurement when the measured value exceeds the accuracy limit. Especially for digital measuring instruments that can measure in units as small as 1/1000, the measured value may not be fixed depending on the measurement target, which can lead to confusion about which value to select.
Depending on the work, an analog measuring instrument may be preferred to determine dimensions in a more intuitive and easy-to-understand manner. In general, choosing between an analog or digital measuring instruments must be decided according to the application and the required accuracy.



Metrological Traceability

In order to guarantee the safety of food products, systems for traceability—from cultivation of raw materials to transporting, processing, packing, and shipping—are being strengthened every year. This is called “food traceability”. Importance is also being placed on traceability in the world of measurement. This way of thinking is known as “metrological traceability” and refers to the initiatives used to prove the accuracy of the values of measurements performed every day.

The Evolution of International Standardization

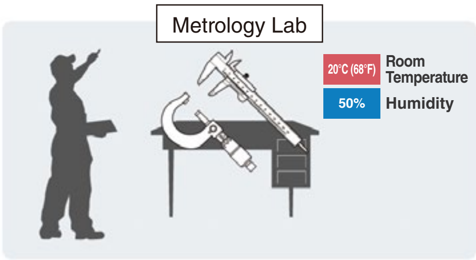
Metrological traceability follows international standards established by international research organizations such as the International Committee for Weights and Measures (CIPM) as well as national standards established by research institutes in each country. With the globalization of the economy, conformity with such standards is in high demand.
Under the International Committee for Weights and Measures, a research organization called the International Bureau of Weights and Measures (BIPM) is working on basic research into the International System of Units (SI).
Complying with international standards has become imperative amid the globalization of manufacturing activities. Today, internationally and mutually approved metrological traceability is essential for dimensional measurement results to be recognized as being universal regardless of where they were generated.

Measurement Environment

Variations in the environment can affect measurement results. For example, a temperature change can cause deformation in the materials, and dust and particles in the air can produce friction in the moving parts of the measuring instrument. This section introduces the environmental requirements for performing measurements.

Room Temperature

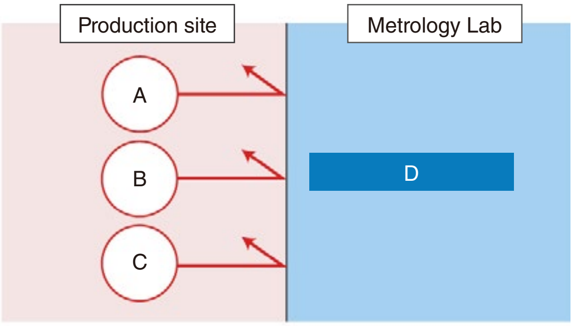
In order to perform reliable measurements, it is necessary to ensure that the environment is appropriate for performing measurements. The key factors for the measurement environment are: temperature and cleanliness. ISO has defined the reference temperature for measurement as 20°C 68°F.
Any material may undergo thermal expansion due to changes in temperature. As such, the temperature in any room where precise measurement is necessary must be strictly controlled.



Temperature control is necessary for precise measurements.

Cleanliness

The cleanliness of the room where measurements are performed is another important condition when it comes to ensuring precise measurements. If dust or dirt in the air gets inside the measuring instrument, the instrument's moving parts may be damaged. Also, foreign matter may interfere with accurate measurements if any gets between the measurement target and the measuring instrument.
The types of foreign matter found at production sites include grains of sand and metal chips generated during processing, as well as fibers from work clothes and hair. These types of foreign matter may result in errors at the sub-micrometer level or higher, so it is necessary to ensure that the environment is cleaned on a daily basis.



A: Dust B: Oil C: Chips from machining D: Clean environment

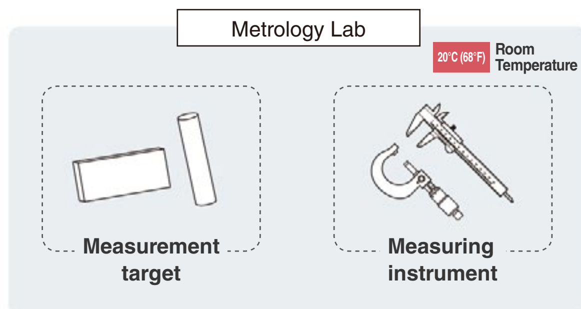
Temperature and Measurement

Because an object's volume changes due to thermal expansion, its length changes with temperature fluctuations. Therefore, even if two objects have the same specifications, the lengths may vary depending on the temperature at the time of measurement. The rate of thermal expansion also differs depending on the material, as shown in the following table.

Examples of materials and thermal expansion coefficients

Material	Thermal expansion coefficient × 10^{-6}
Aluminum	23
Brass	17.5
Polyethylene	100 to 200

When measuring an object's length, it is necessary to consider the temperature conditions. The International Organization for Standardization has set the reference temperature for measurement at 20°C 68°F. When the measurement target is brought in from a location with a different temperature, it is generally necessary to allow the target to adjust to the new temperature for at least an hour. In addition, if the temperature at the time of measurement is not 20°C 68°F, it is necessary to calculate the error and make the corresponding corrections. Thermal expansion does not occur in just the measurement target. It also occurs in the measuring instrument. Therefore, it is necessary to maintain the reference temperature for both the measurement target and the measuring instrument.



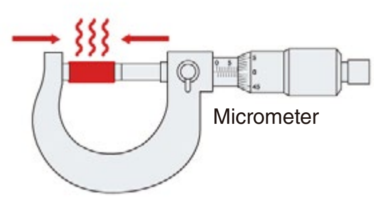
Temperature adjustment is necessary.

Material Stiffness

An object's ability of resist deformation when an external force is applied is called "stiffness". Also, the object's ability to return to its original shape when the external force is removed is called "elastic deformation". The ratio of external force to elastic deformation is called "Young's modulus".

Examples of materials and Young's modulus

Material	Young's modulus (× 10^{10} N/m^2)
Aluminum	7.03
Brass	10.06
Polyethylene	0.04 to 0.13



Tightening the screw excessively may lead to deformation of an object with a low Young's modulus.

The lower Young's modulus is, the lower the stiffness is, indicating that the material can be easily deformed. For example, if an object with a low Young's modulus is measured with a micrometer, the object may be deformed if the screw is tightened excessively, which may prevent accurate measurement.

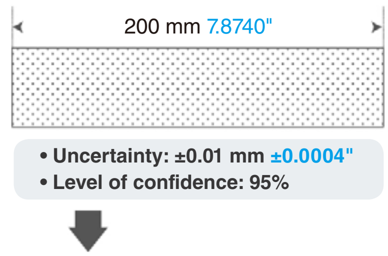
Assessing Measurements

Assessing measured values is no simple matter. A measured value is never a true value — some amount of error is always included. As such, it is difficult to assess the reliability of any one measurement. Conventionally, reliability was evaluated based on measured value bias (systematic error) and variations (random error) while using the true value as a reference.

However, the measured value assessments are not uniform, making it difficult to determine the true value. Therefore, a method for judging the reliability of the measurement results from a statistical perspective was devised. This is the concept of "uncertainty". The range in which the true value exists is calculated by using statistical processing to estimate the error.

For example, the length of a processed metal bar can be expressed as being measured as 200 mm 7.8740" long, with an uncertainty of ±0.01 mm ±0.0004" and a level of confidence of 95%. This indicates that the true value is between 199.99 7.8736" and 200.01 mm 7.8744" with a level of confidence of 95%.

This approach is used in international standards such as those of the International Organization for Standardization (ISO).

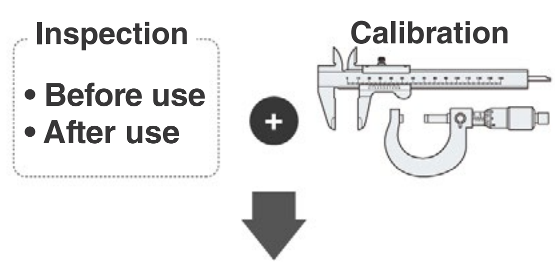


True value is between 199.99 7.8736" and 200.01 mm 7.8744" with a level of confidence of 95%

Calibration and Periodic Inspection

The Meaning of Calibration

Calibration means using a measurement standard to determine the relationship between the value displayed by the measuring instrument and the true value. The reliability of a measuring instrument can be guaranteed by calibrating it according to a measurement standard. Generally, calibration is performed twice: before and after using the measuring instrument. If a measuring instrument is used continuously and is calibrated periodically, the interval must be determined in advance and strictly followed. This is called the "calibration interval". In determining the interval, refer to the manufacturer's recommendations while also judging the interval according to the measuring instrument's frequency of use.



Basic rules of reliable measurement

ISO 9001-Based Measuring Instrument Management

In recent years, thorough control of measuring instruments has been insufficient, and obtaining certification by a certification body through control based on a management system has become necessary. This is due to the need to prove that industrial product specifications are reliable according to international standards. Specifically, measuring instrument management, according to ISO 9001, is spreading because companies want to ensure appropriate measuring instrument control.

Today, every company attempts to support metrological traceability, and it is necessary to prove to customers the reliability of measurements, so calibration based on ISO 9001 can be found at all manufacturing worksites regardless of the scope of the company.

Calibration Methods

There are multiple ways to perform calibration. Select the optimal method that matches the conditions within your company.

Calibration type	Overview
In-house calibration	Certify a calibration specialist in-house, determine details such as the calibration interval and the calibration criterion, and then perform calibration. (Examples: Vernier calipers, micrometers, etc.)
External calibration (Off-site calibration)	Send the measuring instrument to a calibration organization outside of the company, and have that organization perform the calibration. (Examples: Gauge blocks, dial gauges, etc.)
On-site calibration	Submit a request to a calibration organization to have them send a calibration specialist to your company in order to perform on-site calibration. (Examples: Optical comparators, coordinate measuring machines, etc.)

Periodic Inspections and Instrumental Errors

Like any other machine, continued use of a measuring instrument leads to wear in various parts such as the gears and measurement surfaces. This may make it impossible to maintain the accuracy of the measuring instrument.

The accuracy of a measuring instrument is called its “instrumental error”. Because instrumental error has an effect on variations in the measured values, it is absolutely necessary to check for problems through periodic inspection (periodic calibration).

Measurement System Types and Characteristics

It is important to select a measuring instrument that is well suited for the intended application, meets the installation and accuracy requirements, and is convenient to use. This section introduces various measuring instruments as well as the characteristics and construction of each.

Vernier Calipers/Height Gauges (Depth Gauges)

Overview

Hand calipers are measuring instruments that can measure a variety of items such as length (outer shape), inner diameter, and level differences. Their use is widespread in manufacturing due to their ease of use and their ability to perform measurements with comparatively high accuracy. Recently, digital hand calipers have become increasingly popular.
The most commonly used hand calipers are M-type hand calipers and BC-type hand calipers, which are used to measure large objects.

Construction and Applications

- Length (outer shape) measurement: Close the large outer jaws on the measurement target, and then read the values from the main scale and the Vernier scale.
- Inner diameter measurement: Insert the small inner jaws inside the measurement target, and widen the jaws until there is no gap between the jaws and the target to perform the measurement.
- Level difference measurement: Insert the depth probe or a step into the hole or level difference to perform measurement.

How to use Vernier calipers

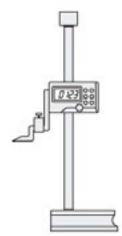
1. During measurement, grasp the main scale and move the slider with your thumb to close the large outer jaws around the target. Pushing the slider too forcefully will cause the jaws to be at an angle, which will prevent accurate measurement. Also, when measuring a cylinder, be sure to firmly close the parallel surfaces of the large outer jaws around the target.
2. Read the gradations on both the main scale and the Vernier scale on the hand caliper. The Vernier scale divides one gradation of the main scale into 20 gradations. In general, this enables measurements in units as small as 0.05 mm 0.002".
3. Read the Vernier scale from the left at the position where it overlaps with the gradation of the main scale.

Handling Precautions

- Applying more force to the slider than necessary during measurement may lead to errors caused by the large outer jaws becoming bent.
- With the scales at zero, the normal state is where no light leaks from the large outer jaws when they are closed.
- Exercise particular care when handling the small inner jaws and the depth probe, as these parts may deform easily if handled roughly.
- Periodically confirm whether the measurement accuracy has been maintained. One simple and useful method is to use a gauge block to perform measurements.
- The calibration interval for hand calipers, height gauges, and depth gauges is 6 months to 2 years.

Height Gauges and Depth Gauges

Height gauges and depth gauges can be considered relatives of hand calipers. When combined with a dial gauge, a height gauge can be used to measure height. Depth gauges, meanwhile, are used to measure level differences.


Height gauge


Depth gauge

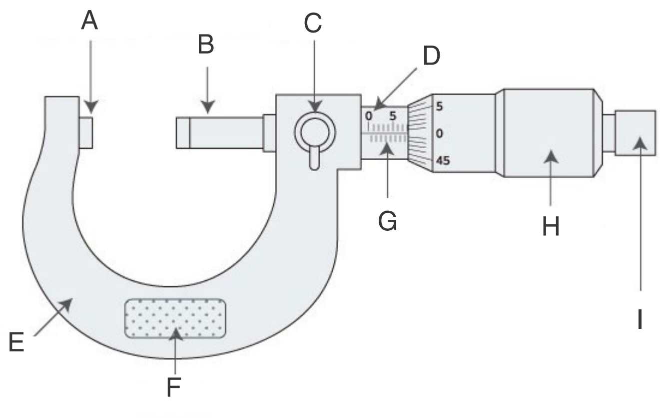
Micrometers

Overview

A micrometer is a tool that measures the size of a target by enclosing it. Some models are even able to perform measurements in units of 1 μm. Unlike hand calipers, micrometers adhere to Abbe's principle, which enables them to perform more accurate measurements.
In general, the term "micrometer" refers to outside micrometers. A variety of other types of micrometers also exist according to different measurement applications. Examples include inside micrometers, bore micrometers, tube micrometers, and depth micrometers. The measurable range differs every 25 mm 0.98"—such as 0 to 25 0.98" and 25 to 50 mm 0.98" to 1.97"—depending on the size of the frame, so using a micrometer that matches the target is necessary. Recently, digital micrometers have become incredibly popular.

* Abbe's Principle
This principle states that, "In order to improve measurement accuracy, the measurement target and the scale of the measuring instrument must be placed in a collinear fashion in the measurement direction". With micrometers, the scale and the measurement position are collinear, so these instruments follow Abbe's principle. As such, micrometers can be said to have high measurement accuracy.

Construction and Applications

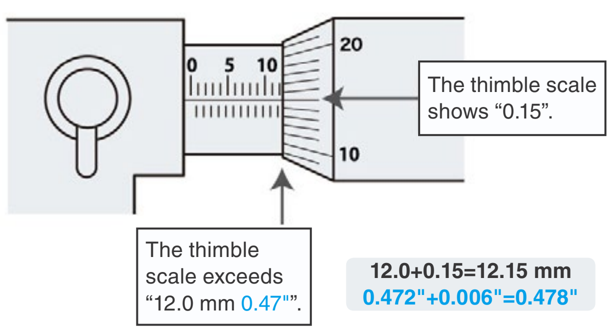


A: Anvil B: Spindle C: Clamp D: Sleeve
E: Frame F: Heat-resistant plate G: Scale H: Thimble I: Ratchet stop

- Place the target between the anvil and the spindle, and then turn the thimble to lock the target between the two surfaces.

How to Use a Micrometer

1. Before measurement, wipe down the anvil and spindle surfaces with a clean cloth. This removes dirt and dust from the surfaces, which enables accurate measurements.
2. To hold the micrometer, hold the heat-resistant plate on the frame with the thumb and index finger on your left hand, and pinch the thimble between the thumb and index finger on your right hand.
3. Grip the target between the anvil and the spindle, turn the ratchet stop until it slips, and then read the value.
4. Read the value from the main scale on the sleeve and the scale on the thimble. Use the line on the right edge of the sleeve to read the value in units of 0.5 mm 0.02". You can then use the scale at which the center line on the thimble (scale) lines up to read the value in units of 0.01 mm 0.0004".



Handling Precautions

- Use a gauge block or a dedicated gauge to calibrate a micrometer. In order to perform accurate measurements, the anvil surface must always be flat. After multiple measurements are performed, the surface may become no longer flat due to wear and the accumulation of dirt. Therefore, periodically use a part known as an optical flat to check whether the surface is flat according to the displayed Newton’s rings.
- When measuring a metal target and when performing calibration with a gauge block, exercise caution with respect to thermal expansion. Whenever possible, avoid holding metal with bare hands, or use gloves that do not transmit heat and are designed for precision work.
- The calibration interval of micrometers is 3 months to 1 year.

Optical Comparators

Overview

Optical comparators are a type of optical measuring instrument. The measurement principle is similar to that of optical microscopes. The target is placed on the stage, and a light is shined on the target from underneath. This causes the target’s profile, or shadow, to be projected on the screen. A telecentric optical system is used to enable accurate measurements.

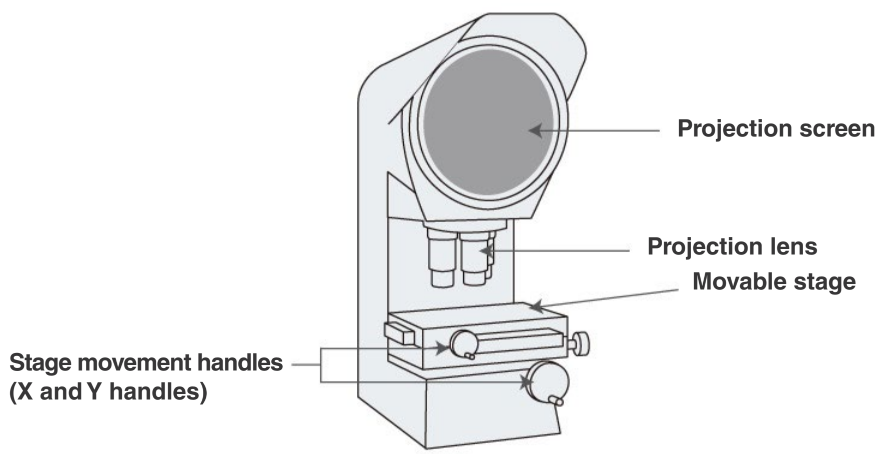
Optical comparators were originally developed to inspect the outlines of targets. Models equipped with measurement functions appeared later. Some large optical comparators have screen diameters that exceed 1 m 3.3'.

The following are some advantages of optical comparators.

- Non-contact measurement of target.
- Measurement is possible even for targets with small or complicated shapes.
- Unlike measuring microscopes, there is no need to look through an ocular lens, which makes it possible for multiple people to perform observations at the same time.

The use of optical comparators is widespread in the inspection and measurement of items such as electronic components and precision components. Conventionally, time and effort was required for datum referencing and target positioning.

Construction and Applications



How to Use an Optical Comparator

1. Place the target on the stage.
2. Position the scale on the zoomed image projected on the screen, and then measure the dimensions. The XY stage can also be used to measure the dimensions according to the amount of stage movement.
3. Some optical comparators use a scale that is read by pinching the target. With such optical comparators, the length is read from a scale between a pair of reading lines.

Handling Precautions

- The calibration interval for optical comparators is 6 months to 3 years.

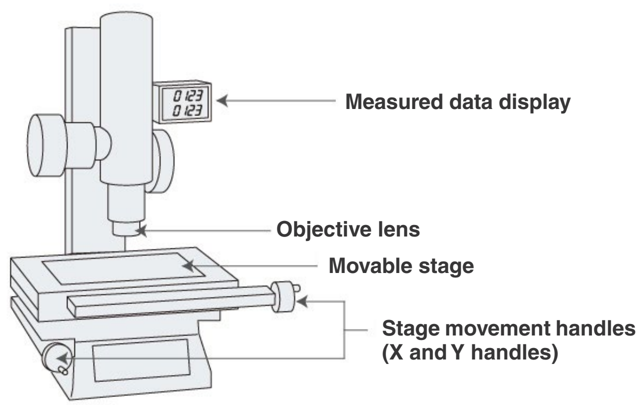
Measuring Microscopes

Overview

Measuring microscopes combine an optical microscope with a table capable of precise movement to measure targets. As with optical comparators, a telecentric optical system is used to enable accurate measurements. Measurements can be performed in a non-contact manner, so there is no risk of damaging the target.
Different types of measuring microscopes are available to match different applications. Examples include toolmaker's microscopes, factory-use measuring microscopes, and general-purpose measuring microscopes. The characteristics of these microscopes are outlined below.

- Toolmaker's microscopes: Originally used to measure tools, these were the first measuring microscopes.
- Factory-use measuring microscopes: These microscopes are suited to the measurement of small, processed parts and similar items.
- General-purpose measuring microscopes: These microscopes support a wider range of applications than toolmaker's microscopes and can measure large objects.

Construction and Applications



How to Use a Measuring Microscope

1. Place the target on the stage.
2. As with general-purpose optical microscopes, subject the target to transmitted light or reflected light, and then align the edge of the shadow with the reference lines to perform measurement. Use different lighting (such as backlighting and coaxial illumination) depending on the target.
3. The measured values can then be output as various types of CAD data.

Handling Precautions

- Just as with general-purpose microscopes, measuring microscopes must be used in an environment free of dust. The stand on which the measuring microscope is installed must also be level and free of oscillations.
- After use, cover the measuring microscope to prevent dust from adhering to it.
- The calibration interval for measuring microscopes is 1 to 3 years.

The Latest Measuring Microscopes

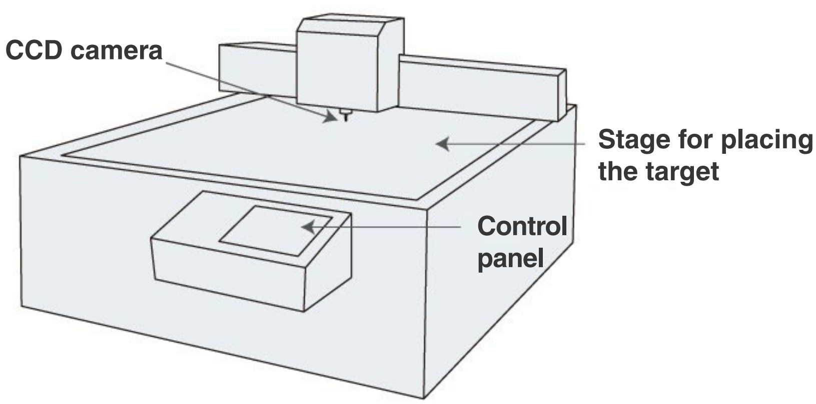
Recent models of measuring microscopes are able to instantly measure dimensions without XY stage movement or focusing, enabling the measurement of many objects in a short amount of time.

Optical CMMs

Overview

An optical CMM, similar to optical comparators and measuring microscopes, is a non-contact instrument that uses images to perform measurements.
Optical CMMs are also known as CNC image measuring machines, where “CNC” is an abbreviation of Computer Numerical Control. As the name suggests, these machines use image processing technology to perform automatic measurements that are both fast and highly accurate. As factory automation at manufacturing sites has steadily progressed, so has the rapid development of these measuring instruments.
Optical CMMs are highly valued not only for their highly accurate measurements but also for their ability to check for defective parts on manufacturing lines. Recent models use highly accurate CCD cameras to enable the observation of color images. Meanwhile, the evolution of the associated software has made it possible to perform varied edge detections and to support complicated calculations.

Construction and Applications



How to Use an Optical CMM

1. Place the measurement target in the metrology lab for at least 5 hours before measurement to allow the target to adjust to room temperature (generally 20°C 68°F). This will prevent errors due to thermal expansion.
2. Place the target on the stage, and scan it to capture an image that will be used for detecting the edges.
3. Some models can also perform auxiliary measurements using laser light or a touch probe.
4. The measured values can then be output as various types of CAD data.

Handling Precautions

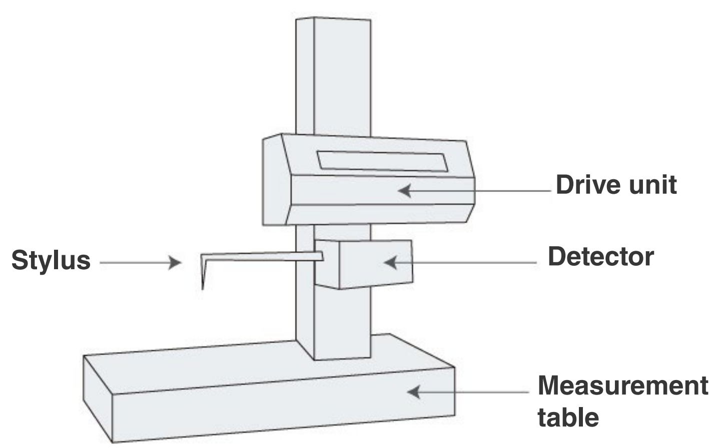
- Use a calibration chart to periodically check the auto-focus accuracy and other performance factors.

Profile Measurement Systems

Overview

Profile measurement systems measure and record the profile of a target by tracing the surface of the target using a stylus. Some instruments can even be used as surface roughness meters. Models with computer numerical control (CNC) are capable of measuring the angles, radiuses of arcs, height differences, and screw thread pitches. These instruments are ideal for measuring minute shapes such as screw threads and thin films in the order of micrometers.
In recent years, profilometer models have been developed that use a laser instead of a stylus to measure complex shapes by tracing the profile in a non-contact manner. Some models are even able to perform measurements of both the top and bottom surfaces.
These instruments are mostly used in the creation of prototypes to check whether the specifications match the design drawings. They are also applied in reverse engineering.

Construction and Applications



How to Use a Profile Measurement System

1. Attach the stylus to the main unit.
2. Perform measurements according to the handling procedure (such as positioning and origin setting).
3. Use a jig such as a Y-axis table or a rotating table to automate the measurement.
4. The measured data can then be converted and used as various types of CAD data.

Handling Precautions

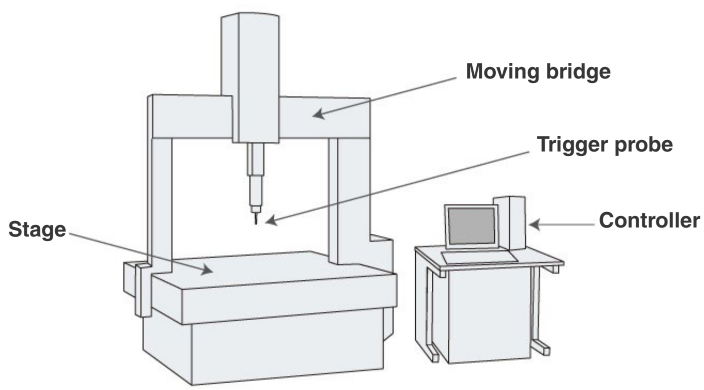
- Select a stylus suitable for the shape of the target and the purpose of the measurement.
- Especially for models that use laser, measurements must be performed in an environment free of dust.
- In order to perform correct measurements with high accuracy, use a jig or other tool to correctly position the target on the measuring instrument.
- Calibration is required before using the instrument. Use a dedicated kit to perform the calibration.

Coordinate Measuring Machines

Overview

Conventionally, measurements were taken visually using an optical comparator or a measuring microscope. This required both experience and skill to operate the instruments, as well as time to perform the actual measurement.
On the other hand, a coordinate measuring machine measures the height, width, and depth of the target using image processing technology. In addition, such machines can automatically measure the target, record the measured data, and obtain special values through the use of various calculations.
Coordinate measuring machines are either contact models, known as touch probes, which use a spherical object to perform measurements, or non-contact models, which use other methods such as lasers. Some models designed for the automotive industry can even measure targets larger than 10 meters 32.8' in size.
One example application is measuring the difference between a target and its diagram for molds, such as those used with automotive parts and for 3D objects such as mechanical parts. Following the recent spread of 3D printers, there is a new trend toward measuring the dimensions of existing parts and standard parts with a coordinate measuring machine, and creating prototypes based on this data with a 3D printer.

Construction and Applications



How to Use a Coordinate Measuring Machine

1. Place the measurement target in the metrology lab for at least 5 hours before measurement to allow the target to adjust to room temperature (generally 20°C 68°F). This will prevent errors due to thermal expansion.
2. Perform measurements by following the handling procedure of the machine.
3. The measured data can be imported into a PC where it can be used as 3D-CAD data.

Handling Precautions

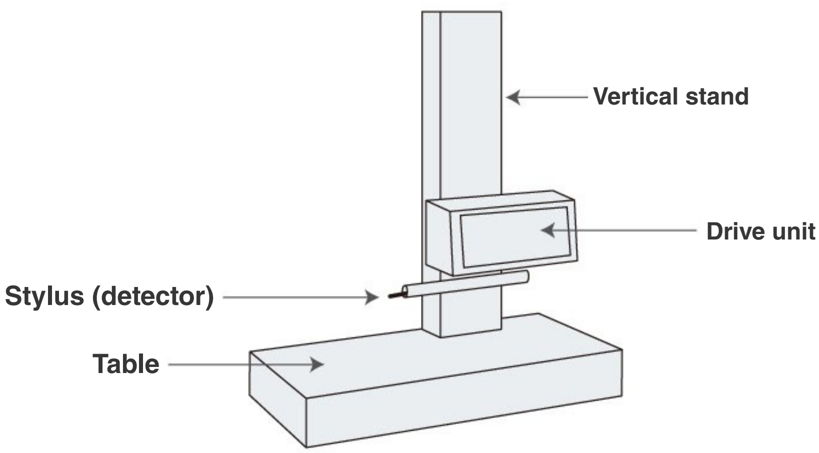
- Although some models can perform measurements on the order of 0.1 μm, correct usage and management are vital for measurement accuracy.
- Verify that the moving parts move horizontally and vertically during use. Also, use a measurement standard or a similar object to check for indication errors.
- In order to perform accurate measurements, allowing the temperature of the target to adjust to room temperature in the metrology lab is critical. Alternatively, the measurement parameters must be set to correct for any temperature difference.
- For touch probes, it is important to ensure that the probe contacts the target at a constant speed during measurement.
- The calibration interval for coordinate measuring machines is 6 months to 2 years.

Roughness Meters

Overview

Roughness meters, also called “surface roughness meters”, are instruments that measure the smoothness (degree of roughness) of the surface of a target. The main types of meters use either probes or lasers. Conventionally, the most common models used a diamond probe, but optical types have become more common due to concerns of the diamond probe damaging the surface of semiconductors and similar objects during measurement. Some models can measure both flat and curved surfaces. Recently, models that can display a 3D image of the shape based on the data measured from the surface have also appeared.
Examples of applications of roughness meters include checking for wear on metal surfaces, checking cut surfaces, and checking painting finishes. With more and more electronic components being made using thin film processing, some roughness meters can even perform measurement in the order of nanometers.

Construction and Applications



• Probes commonly use a tip with a radius of 2 μm. However, for precision-machined products, probes with a tip in the 0.1 to 0.5 μm range are also common. Variations in measured values may occur depending on the probe used, so checking in advance whether the tip is appropriate is essential.

How to Use a Roughness Meter

1. With a contact-type roughness meter, surface roughness is measured by tracing the probe across the surface of the target. In contrast, a laser-based non-contact roughness meter emits a laser beam onto the target and detects the reflected light to measure the roughness.
2. The direction of measurement is the key to successful measurement. For example, a processed metal product is generally measured perpendicularly to the processing direction so that the roughness meter can capture the surface characteristics more reliably.
3. Measurement speed is also a key element for accurate measurement. Measurement is first performed slowly, and the speed is increased until no fluctuation occur in the measured values.

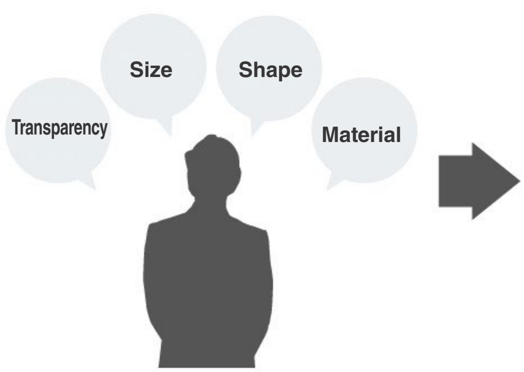
Handling Precautions

• Periodic calibration is required to perform correct measurements.

Selecting a Measurement System

Even for those who know the basics of measuring instruments, including instrument characteristics and precautions, a level of uncertainty about which measuring instrument to choose may still exist. This section introduces a number of approaches to selecting a measuring instrument, such as selecting based on the measurement target or the cost of measuring.

Selecting by Measurement Target



Selecting a measuring instrument that suits the requirements for the measurement target

Is the shape simple or complex?

It goes without saying that the simpler the target shape is—such as with a rectangular solid or a circle—the easier it is to measure the dimensions. A wide variety of measuring instruments—such as rulers, tape measures, Vernier calipers, and micrometers—can also be used for these types of targets. For height measurements, these measuring instruments are used together with a height gauge or a dial gauge.
On the other hand, measuring the dimensions of targets with complex shapes, such as polygons and stars, is more difficult. The measuring instruments that can be used to measure such shapes are also limited. Optical comparators and image dimension measurement systems are best suited to measuring the dimensions of especially complicated shapes. In recent years, instruments have been developed with functions that make it possible to measure details such as the dimensions and angles of complicated shapes just by placing the target on the stage.

Is the material hard or soft?

When very hard targets such as metals and ceramics are pinched between the measuring components of hand calipers or a micrometer, the rate of target deformation is low, so measurement can be considered easy regardless of what measuring instrument is used.
However, when a soft object such as one made out of a synthetic resin is pinched between the measuring components of such instruments, the target will be deformed, making it difficult to perform measurement. In such situations, non-contact measuring instruments are very useful. For example, an image measuring instrument uses a laser light or similar light source to measure the dimensions in a non-contact manner.

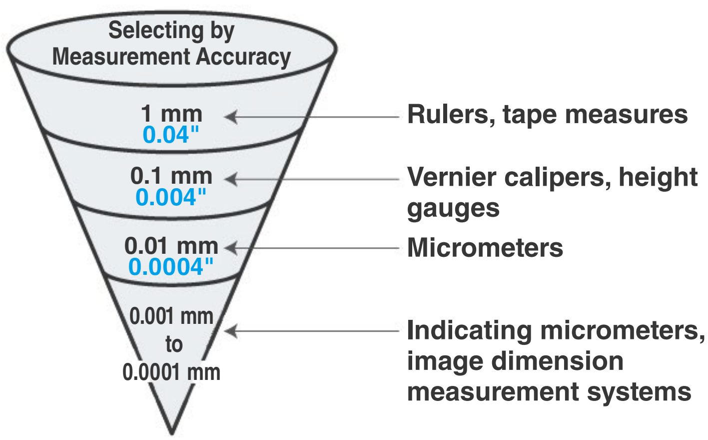
Selecting according to size

Measuring microscopes are effective in measuring extremely small targets with dimensions in the micrometer scale or smaller. The operating principle of measuring microscopes is the same as with regular microscopes, and measurements can be performed in a non-contact manner, so there is no risk of damaging the target.
On the other hand, long scales are used to perform simple measurements of targets as large as a few meters, such as automobiles. A large CNC coordinate measuring machine can be useful for performing precise measurements.

Selecting according to transparency

A wide variety of measuring instruments can be used to measure opaque targets. However, some manipulation is required for measuring targets that have a high transmission ratio, such as when measuring the thickness of a transparent film. Micrometers and other contact-type instruments can measure transparent objects, but these instruments are not suitable for accurately measuring flexible objects such as films.
On the other hand, laser displacement meters and other measuring instruments that use laser beams can perform accurate measurements in a non-contact manner.

Selecting by Scale Unit



1 mm 0.04" Units

The ruler is the most popular measuring instrument that can be used to measure at a scale of 1 mm 0.04" units. Steel and glass rulers are generally used at manufacturing sites. Tape measures are also commonly used, and plant engineers can usually be seen carrying one around. Gauge blocks are often seen at metal processing plants and other manufacturing sites. Block gauges are rectangular solids made of steel whose dimensions and parallelism are guaranteed on the order of 0.1 μm. They are highly valued for their use in dimensional measurements of processed products. One of the advantages of gauge blocks is how they can be combined to create a variety of different lengths.

Selecting a Measurement System

0.1 mm 0.004" Units

Vernier calipers are measuring instruments generally used to perform measurements in units of 0.1 mm 0.004". Their smallest scale is 0.02 mm 0.0008" or 0.05 mm 0.0020". Height gauges can be used to measure heights at this size as well.

0.01 mm 0.0004" Units

Micrometers are frequently used to perform measurements in units of 0.01 mm 0.0004". Based on Abbe's principle, these instruments are designed to perform measurements with high accuracy. Dial gauges are also used quite frequently. Optical comparators can be used to precisely measure multiple measurement points.

0.001 mm 0.00004" Units

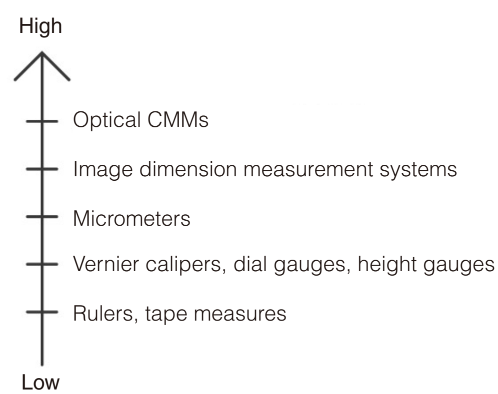
Indicating micrometers are used to perform measurements in units of micrometers. The type most commonly seen today displays measurements digitally. Precautionary measures must be taken to prevent dust and dirt from entering the micrometer during measurement. Using a digital measuring instrument makes it possible even for inexperienced users to perform measurements in units of micrometers.

0.0001 mm 0.000004" Units

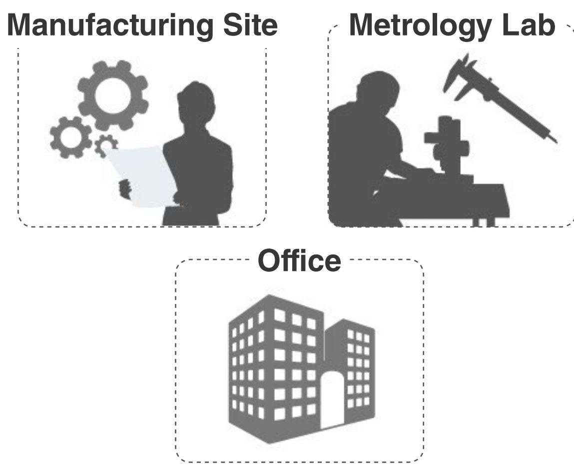
Mechanical measuring instruments may be capable of measurements up to units of 1 μm, but such devices are unable to measure units smaller than micrometers. Laser length measuring instruments, electronic micrometers, and microsensors can be used for such applications. Recently developed measuring instruments such as image dimension measurement systems have also made it easy to perform highly accurate measurements.
The measurement environment is an important factor for achieving correct measurements with such instruments. For example, a metrology lab must be kept at a constant temperature of 20°C 68°F.

Selecting by Cost

Rulers and tape measures are typical low-cost tools. However, they are essential items for manufacturing worksites. Vernier calipers are also relatively low-cost measuring instruments and are useful for measurements in units of 0.1 mm 0.004".
Dial gauges and height gauges are slightly more expensive, but they can measure in units of 0.01 mm 0.0004".
Micrometers have a wide price range and can be selected according to the desired purpose or accuracy of measurement.
In recent years, a number of digital measuring machines have been produced to ensure precision measurement. Some image dimension measurement systems and optical CMMs are expensive. Measuring instruments span across a broad range of costs from low to high, and should be appropriately selected according to the measurement target, application, and desired accuracy.



Selecting by Measurement Environment



Manufacturing Site

Vernier calipers, micrometers, gauge blocks, and other measuring instruments are often found at metalworking and other manufacturing sites. Block gauges are rectangular solids made of steel whose dimensions and parallelism are guaranteed on the order of 0.1 μm. They are highly valued for their use in dimensional measurements of processed products. One of the advantages of gauge blocks is how they can be combined to create a variety of different lengths.
Dust, oil, and processing chips are common at any manufacturing site, so there is always the risk that errors will occur due to measuring instruments becoming dirty or being damaged. It is therefore necessary to keep the work area clean at all times.

Metrology Lab

Micrometers are frequently used to perform measurements in units of 0.01 mm 0.0004". Based on Abbe's principle, these instruments are designed to perform measurements with high accuracy. Dial gauges are also used quite frequently. Laser length measuring instruments, image dimension measurement systems, and similar measuring instruments are used for measurements requiring units smaller than 1 micrometer and make highly accurate measurements easy to perform.
The room temperature in metrology labs is usually regulated, but there is always a risk of thermal expansion for metal targets. In order to perform precise measurements, consideration must be given to adjusting the target to room temperature prior to measurement, and to avoiding holding the target with bare hands.

Office

While the risk of contamination is low compared to manufacturing sites, it is difficult to perform precise measurements like those performed in metrology labs. Furthermore, as measurements may be performed by multiple people, the measuring instruments must be carefully managed in order to reduce the risk of the measurement results being compromised. As such, assigning device managers and defining management standards in advance are required.

Selecting by Application

Length Measurement

Rulers, tape measures, and gauge blocks are commonly used to measure length at manufacturing sites. Long scales are used for targets that are a few meters in length. To perform more precise measurements, instruments such as Vernier calipers, dial gauges, and micrometers are used.

Angle Measurement

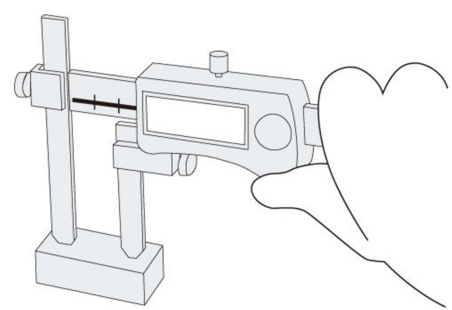
Half circle protractors are useful for measurements in units of degrees. Bevel protractors and optical comparators are used for measurements in units of arcminutes. A measuring instrument known as a sine bar is available for more precise measurements in units of arcseconds. Measurements in units of arcseconds can also be performed by using an angle gauge or an autocollimator.
Engineer’s squares and squareness testers are available tools for checking perpendicularity.

Bore Diameter Measurement

Vernier calipers are used to measure the diameter of holes in objects. There are also dedicated inner diameter measuring instruments.
Tube micrometers, cylinder gauges, small diameter measuring instruments, and plug gauges are used to measure ring-shaped targets with large diameters. Electronic micrometers and air micrometers are used to perform more precise measurements.
Measuring instruments such as optical comparators, industrial microscopes, and image dimension measurement systems are useful when precise optical measurements are needed.

Coordinate Measurement

Off-center Vernier calipers, hole pitch gauges, height gauges, and pin gauges are used to measure coordinates such as the positions of holes in workpieces.
Measuring instruments such as optical comparators, industrial microscopes, 2D/3D measuring instruments, and image dimension measurement systems are useful if precise optical measurements are needed. Standard optical interferometers are used for ultra-precise measurements such as for semiconductors.



Selecting by Measurement Speed

Accurate Measurement with Manual Operation

Vernier calipers and micrometers can be used to perform accurate measurements, but doing so takes time and effort. In order to perform more accurate measurement, it is necessary to perform measurements multiple times. When there are many parts to measure, this can take a long time, so these instruments can be considered not well suited for such measurement operating conditions.

Fast Measurement with Automatic Operation

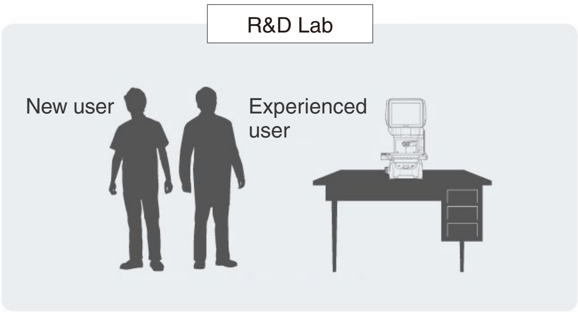
Using an image dimension measurement system makes it possible to measure dimensions in multiple locations on complicated parts at the same time. There is no need to perform measurements multiple times, and measurements can be performed quickly even for multiple parts.

Measurements Grouped by Work

Measurements are made at various points in the manufacturing process. This page introduces the key points and precautions for measuring in the course of different operations, such as R&D and prototype evaluation.

Research and Development

Highly accurate digital measuring instruments are often used in research and development. Some of these measuring instruments can perform highly accurate measurements in units as small as 10 nm. However, prioritizing top-of-the-line accuracy is not appropriate. In selecting a measuring instrument, consideration of the purpose and the required accuracy is critical.
Before using a measuring instrument, check the instrument's characteristics and functions, and then perform measurement according to the correct procedure and under correct management.



***Key point: When selecting a measuring instrument, usability should take precedence over precision and performance**

Examples of Measuring Instruments Used

- Measuring microscopes
- Optical CMMs
- Profile measurement systems
- Coordinate measuring machines
- Roughness meters
- X-ray CT machines
- Roundness measuring instruments

Key Points for Selecting a Measuring Instrument

- Assume that the development tasks will change, so consider in advance whether the instrument is intended for general use or for a specific task.
- There are many situations in which measurements must be performed on multiple experiment samples, so a measuring instrument that can perform measurements automatically and quickly is useful.
- Precision measuring instrument that require specialized knowledge and technical skill to operate can compromise the availability of measurements. It is important to select a measuring instrument that is as easy to use as possible in order to enable even new users to perform measurements easily.

Precautions for Measurements

- Precise measurements must be performed in an environment with a constant temperature, humidity, and cleanliness, such as in a thermostatic chamber. If temperature regulation is difficult, it is necessary to calculate errors based on the thermal expansion coefficient and to determine the value at the reference temperature.
- Most measuring instruments are expensive, so careful handling and management are critical. Select an individual to be in charge of managing the measuring instrument beforehand, and establish handling procedures that are shared among all users of the instrument. After use, clean the instrument according to the cleaning procedure.
  Additionally, because most often a limited number of measuring instruments will be used by multiple individuals, a reservation system for using the instruments is common. Such procedures should be put in place when adopting the measuring instrument.

Prototype Evaluations

The main applications of measuring instruments at prototyping sites are the evaluation of the materials used for the prototypes and of the prototypes themselves. Generally speaking, there can be anywhere from tens to hundreds of prototypes, and not only must measurement be performed accurately and efficiently, but the data must also be shared with all members of the project.
Vernier calipers and micrometers are often used to perform dimensional measurements. However, due to the increased need for precise measurements in recent years, measuring instruments such as measuring microscopes, surface roughness meters, profile measurement systems, and coordinate measuring machines have become common. There is also a growing need to be able to measure complex shapes in addition to ensuring improved accuracy.
What to inspect during mass production and the number of inspections to perform are both determined during prototype evaluation. Therefore, using the same measuring instruments for inspections in mass production as those used in prototype evaluation makes it possible to reduce errors.

*** Choose a measuring instrument that offers both efficiency and accuracy even with limited staff**

Examples of Measuring Instruments Used

- Vernier calipers
- Micrometers
- Measuring microscopes
- Roughness meters
- Optical CMMs
- Profile measurement systems
- Coordinate measuring machines

Key Points for Selecting a Measuring Instrument

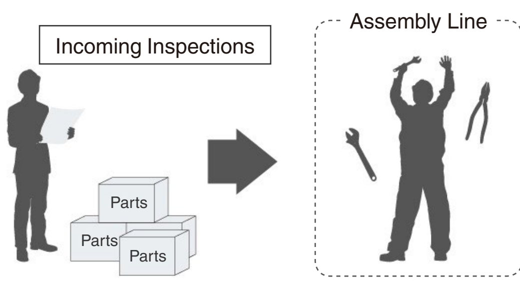
- It is common for there to be numerous prototypes, so the measuring instrument should ideally make it possible for anyone to perform fast, simple, and accurate measurements.
- It is common to measure multiple types of parts with complicated shapes, so a measuring instrument that can be easily configured is useful.
- It is essential to select a measuring instrument that enables inspections during mass production and that can easily be installed on a production line.

Precautions for Measurements

- During prototype evaluation, many people may evaluate a large number of prototypes, so proper management of the measuring instruments is important.
- If the processing machines are located in a different place than where prototype evaluation is performed, errors may arise in dimensional measurements performed in these two locations due to environmental differences such as temperature variations. Measurement conditions should match the conditions used in mass production.

Incoming Inspections

Incoming inspections of externally purchased materials and parts are performed during the processing and assembly of products. The time and work required vary greatly between full inspections and random inspections, so the measuring instruments used also vary.
Generally, the required locations are measured according to quality assurance documents and drawings supplied with the received items. Non-conforming parts are detected during this measurement process, which prevents the parts from being released onto the assembly line. If non-conforming parts are mixed with good parts, a full inspection will be required. What's more, any non-conforming part used in a completed product shipped to customers may lead to complaints. For these reasons, it is important to perform measurements during incoming inspections.



*** The purpose of these inspections is to prevent non-conforming parts from being released onto the line.**

Examples of Measuring Instruments Used

- Metal scales
- Vernier calipers
- Micrometers
- Gauge blocks
- Measuring microscopes
- Coordinate measuring machines

Key Points for Selecting a Measuring Instrument

- Received parts must often be used immediately in product assembly, so inspections must be performed quickly. Therefore, measuring instruments that can measure multiple points quickly and accurately are absolutely necessary.
- Because many different types of parts are received, measuring instruments with easily configured measurement settings are very useful.

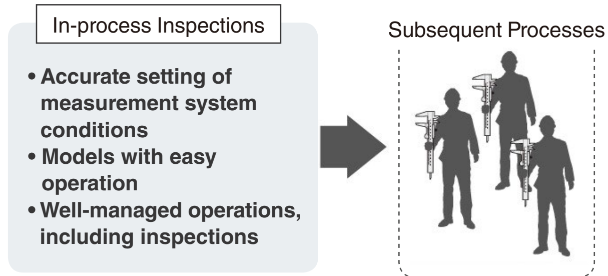
Precautions for Measurements

- To ensure work efficiency and measuring instrument quality control, clarify the storage location used for the measuring instruments, and the person in charge of managing the instruments.
- When measurement will be performed by multiple individuals, standardization of the measurement methods should be promoted. For example, when performing measurements with hand calipers and micrometers, care must be taken to ensure measurements are performed with the same contact pressure.
- Differences may arise between the values obtained in inspections performed by external suppliers and the values obtained during incoming inspections. In such situations, it is absolutely necessary to not only standardize measurement methods within the company but also to match the measurement methods used by the external supplier. Depending on the situation, create statistical data such as a stratified scatter plot to clarify the differences in measured values between measuring instruments, individuals performing the measurements, and external suppliers. Then, consider sharing measurement information and improving measurement methods.

In-Process Inspections, First Article Inspections, Random Inspections, and Tooling Changes

At production sites, performing accurate measurements is important for guaranteeing the quality of all products going through the process. In recent years, the increase in manufacturing of portable electronic devices and transportation equipment has resulted in growing demand for high-precision mechanical processing. Depending on the product, measurements of an order a whole digit higher than conventional methods have become necessary, leading to a need for inspection systems capable of matching these requirements.

For any process, creating products with uniform quality on the basis of predetermined specifications is a necessity. Therefore, it is absolutely necessary to accurately define conditions for measuring instruments within the inspection process and to ensure an environment that enables correct measurements during the operation of the manufacturing line.



* Increased speed of in-process inspections leads to improved efficiency

Examples of Measuring Instruments Used

- Vernier calipers
- Micrometers
- Dial gauges
- Gauge blocks
- Dedicated jigs

Key Points for Selecting a Measuring Instrument

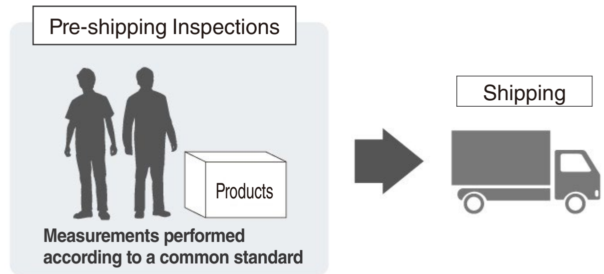
- Instruments must be easy to operate in order to enable proper use by on-site operators.
- The longer an inspection takes, the greater the impact will be on the operation of the manufacturing line, which decreases productivity. Therefore, it is important to select a measuring instrument that can perform measurements quickly and accurately.

Precautions for Measurements

- Specialized jigs are sometimes created in advance at mass production sites. If these jigs are used for a long time, caution must be taken to prevent errors that may arise from factors such as jig wear and contamination. It is essential to perform periodic inspections and to have management methods put in place.
- Wear gloves when handling gauge blocks. Touching the gauges with bare hands may affect the results due to thermal expansion or contamination. Also, gauge blocks must be allowed adequate time to adjust to room temperature as they do not attain temperature equilibration quickly.
- In-process measurement data is used not only in quality inspections but also as statistical data to clarify variations in measured values and to identify the causes of these variations.

Pre-shipping Inspections

In pre-shipping inspections, it is necessary to accurately check whether the dimensions match the specifications in a limited amount of time.



* Does the accuracy meet the requirements of the customer?

Examples of Measuring Instruments Used

- Vernier calipers
- Micrometers
- Gauge blocks
- Optical CMMs
- Coordinate measuring machines

Key Points for Selecting a Measuring Instrument

- Select the measuring instrument based on consideration of the accuracy required by the customer.
- Select a durable instrument that can be easily handled by anyone.

Precautions for Measurements

- Vernier calipers, which can be conveniently used to perform measurements, are sometimes used when inspecting metal parts and such in the limited time available before shipping. Checking for required accuracy and ensuring that there are no potential problems after shipping are critical.
- Measuring instruments are used frequently during pre-shipping inspections. As such, it is essential to manage the measuring instruments to prevent degradations in accuracy. It is necessary not only to check the instruments before use and to clean them after use, but also to establish organizational rules for storing and using instruments as well as other necessary rules.
- When using Vernier calipers, rushing while taking measurements when there is little time can lead to incorrect measurements, such as those caused by tilted measurement surfaces. Furthermore, if the micrometer scale is not read from straight above, parallax may result in the value being read inaccurately. In either case, mastering correct measurement methods and strictly following those methods are essential.

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