SECTION C

Dimensional Measurement

UNIT ONE	Systems of Measurement
UNIT TWO	Using Steel Rules
UNIT THREE	Using Vernier, Dial, and Digital Instruments for Direct Measurements
UNIT FOUR	Using Micrometer Instruments
UNIT FIVE	Using Comparison Measuring Instruments
UNIT SIX	Using Gage Blocks
UNIT SEVEN	Using Angular Measuring Instruments
UNIT EIGHT	Tolerances, Fits, Geometric Dimensions, and Statistical Process Control (SPC)

All of us, no matter what we may be doing, are surrounded by measurement. *Measurement* can generally be defined as the assignment of a value to time, length, and mass. We cannot escape measurement. Our daily lives are greatly influenced by the clock, a device that measures time. The mass or weight of almost every product we buy is measured, and the measure of length is incorporated into every creation of humans, ranging from the minute components of an integrated circuit to the many thousands of superhighway miles extending across a continent.

Measurement, in the modern age, has been developed to an exact science known as **metrology**. As the hardware of technology continues to become more complex, a machinist is increasingly concerned with that branch of the science called *dimensional metrology*. Furthermore, mass production of goods has made necessary very complex systems of metrology to check and control the critical dimensions that control standardization and interchangeability of parts. Components of an automobile, for example, may be manufactured at locations far removed from one another and then brought to a central assembly point, with the assurance that all parts will fit as intended by the designer. In addition, the development and maintenance of a vast system of carefully controlled measurement has permitted manufacturers to locate their factories close to raw materials and available labor. Because of the standardization of measurement, industry has been able to diversify its products. Thus, manufacturers can do what they do best, and manufacturing effort can be directed toward product quality and production at a competitive price. As a result, metrology affects not only the technical aspects of production but also the economic aspects. Metrology is a common thread woven through the entire fabric of manufacturing from the drafting room to the shipping dock. The units in this section illustrate and demonstrate most of the common measuring tools used in machining technology. Even though you may never see all these tools in your experiences, you should study this material carefully, since the subject of precision measurement is common to all the machine shop activities described in this text.

This section also covers the subjects of tolerances, fits, and geometric dimensions and introduces statistical process control (SPC). These topics are equally essential to the modern machinist, especially in the age of computer-assisted manufacturing (CNC and CAM). Much of your work as a machinist will be dedicated to meeting dimensional specifications of the parts that you make, both in part size and part geometry. Meeting tolerance specifications in machining in turn permits the correct fit between parts in precision assemblies and thus the proper performance of these parts and assemblies in complex machines and other equipment.

There is every possibility that your career will be involved with some phase of high-precision computer-controlled machining equipment (CNC) either as an operator, setup person, inspector, computer part programmer, or possibly a manufacturing engineer. Statistical process control (SPC) will play an important part in all phases of computer-assisted manufacturing where high-precision machining production is used. Therefore, the modern machinist must also be familiar with the tools and methods of SPC activities.

MEASUREMENT NEEDS OF THE MACHINIST

A machinist is mainly concerned with the measurement of **length,** that is, the distance along a line between two points (Figure C-1). It is length that defines the **size** of most objects. **Width** and **depth** are simply other names for length. A machinist measures length in the basic units of linear measure

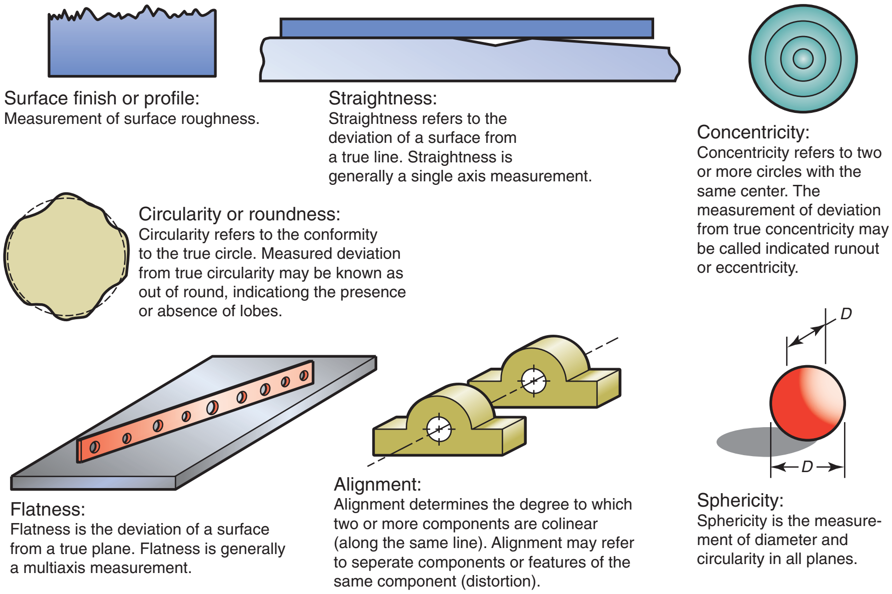


Figure C-1 The measurement of length may appear under several different names.

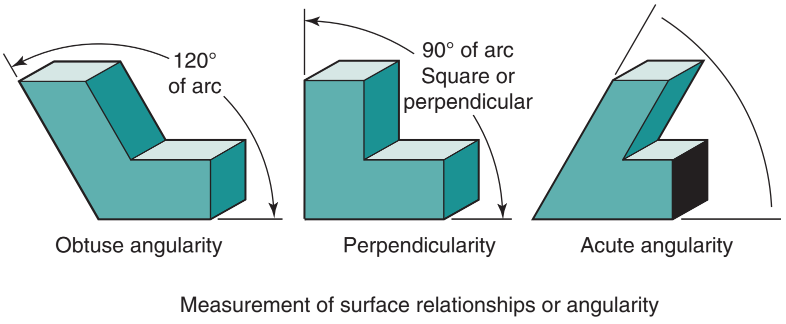


Figure C-2 Measurement of surface relationships, or angularity.

such as **inches, millimeters,** and, in advanced metrology, wavelengths of light. In addition, the machinist sometimes needs to measure the relationship of one surface to another, commonly called **angularity** (Figure C-2).

Squareness, closely related to angularity, is the measure of deviation from true perpendicularity. A machinist will measure angularity in the basic units of angular measure—**degrees, minutes,** and **seconds of arc.**

In addition to length and angularity, a machinist also needs to measure such things as **surface finish, concentricity, straightness,** and **flatness.** He or she also occasionally sees measurements that involve circularity, sphericity, and alignment (Figure C-3). However, many of these more specialized measurement techniques are in the realm of the inspector or laboratory metrologist and appear infrequently in general machine shop work.

GENERAL PRINCIPLES OF METROLOGY

A machinist has available many measuring tools designed for use in different applications. However, not every tool is equally suited for a specific measurement. As with all the other tools of a machinist, selecting the proper measuring tools for the specific application at hand is a primary skill. The successful outcome of a machinist's work may indeed depend on the choice of measuring tools. In this regard, a machinist must be familiar with several important terms and principles of dimensional metrology.

Accuracy

Accuracy in metrology has a twofold meaning. First, accuracy can refer to whether or not a specific measurement is actually its stated size. For example, a certain drill has its size stamped on its shank. A doubtful machinist decides to verify the drill size using a properly adjusted micrometer. The size is found to be as stated. Therefore, the size stamped on the drill is accurate. Second, accuracy refers to the act of measurement itself with regard to whether or not the specific measurement taken is within the capability of the measuring tool selected. A machinist obtains a drill with the size marked on the shank and decides to verify it using a steel rule. The edge of this rule with the finest graduations is selected; the machinist then lays the drill over the marks. Sighting along the drill, he discovers that it is really three graduations, on his rule, smaller than the size stamped on the shank. He then reasons that the size marked on the drill must be in error. In this example, the act of measurement is not accurate because the inappropriate measuring tool was selected and the improper procedure was used. **User accuracy** is also an important consideration. If when the machinist measured the drill with his micrometer, as described in the first example, he did not bother to confirm the accuracy of the instrument prior to making the measurement, an inaccuracy that can be attributed to the user may have resulted.

Precision

The term **precision** is relative to the specific measurement being made, with regard to the degree of exactness required.

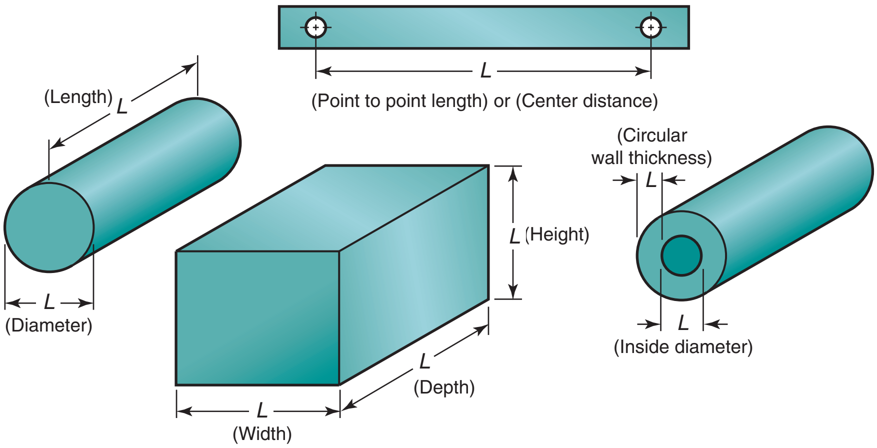


Figure C-3 Other measurements encountered by the machinist.

For example, the distance from the earth to the moon, measured to within one mile, would indeed be a precise measurement. Likewise, a clearance of five thousandths of an inch between a certain bearing and journal might be precise for that specific application. However, five thousandths of an inch clearance between ball and race on a ball bearing would not be considered precise, as this clearance would in fact be only a few millionths of an inch. **There are many degrees of precision dependent on application and design requirements.** For a machinist, any measurement made to a degree finer than one sixty-fourth of an inch or one-half millimeter can be considered a **precision measurement** and must be made with the appropriate precision measuring instrument.

Reliability

Reliability in measurement refers to the ability to obtain the desired result to the degree of precision required. Reliability is most important in the selection of the proper measuring tool. A certain tool may be reliable for a certain measurement but totally unreliable in another application. For example, if it were desired to measure the distance to the next town, the odometer on an automobile speedometer would yield quite a reliable result, provided a degree of precision of less than one-tenth mile was not required. On the other hand, to measure the length of a city lot with an odometer would be much less likely to yield a reliable result. This difference is explained by examining another important principle of metrology, that of the discrimination of a measuring instrument.

Discrimination

Discrimination refers to the degree to which the basic unit of length of a measuring instrument is divided. The mile on an automobile odometer is divided into 10 parts; therefore, it discriminates to the nearest tenth of a mile. An inch on a micrometer, one of the most common measuring instruments of a machinist, is subdivided into 1000 or, in some cases, 10,000 parts. Therefore, the micrometer discriminates to .001 or .0001 of an inch. If a measuring instrument is used beyond its discrimination, a loss of reliability will result. Consider the example cited previously regarding the measurement of a city lot. Most lots are less than one-tenth of a mile in length; therefore, the discrimination of the auto odometer for this is not sufficient for making a reliable measurement.

10:1 Ratio for Discrimination

In general, a measuring instrument should **discriminate 10 times finer** than the smallest unit that it will be used to measure. The odometer, which discriminates to a tenth of a mile, is most reliable for measuring whole miles. To measure the length of a city lot in feet requires an instrument that discriminates to at least one-tenth of a foot. Since most surveyors' measuring tapes used for this application discriminate to tenths and in some cases to hundredths of a foot, they are an appropriate tool for the measurement.

Position of a Linear Measuring Instrument with Regard to the Axis of Measurement

A large portion of the measurements made by a machinist are linear in nature. These measurements attempt to determine the shortest distance between two points. In order to obtain an accurate and reliable linear measurement, **the measuring instrument must be exactly in line with the axis of that measurement.** If this condition is not met, reliability will be in question. The alignment of the measuring instrument with the axis of measurement applies to all linear measurements (Figure C-4). The figure illustrates the alignment of the instrument with the axis of measurement using a simple graduated measuring device. Only under the reliable condition can the measurement approach accuracy. Misalignment of the instrument, as illustrated in the unreliable situation, will result in inaccurate measurements.

Responsibility of the Machinist in Measurement

The units in this section discuss most of the common measuring tools available to a machinist. The capabilities, discrimination, and reliability of the tools as well as procedures for

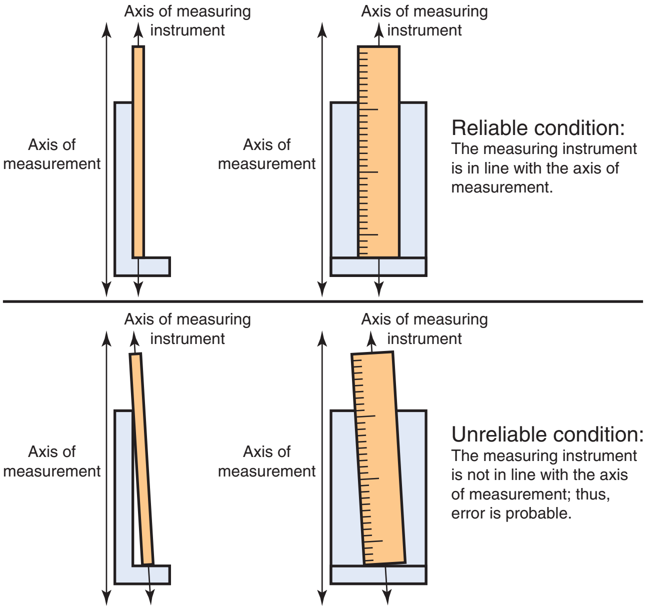


Figure C-4 The axis of a linear measuring instrument must be in line with the axis of measurement.

using them are examined. It is, of course, the responsibility of a machinist to select the proper measuring instrument for the job at hand. When faced with a need to measure, a machinist should ask the following questions:

1. What degree of accuracy and precision must this measurement meet?
2. What degree of measuring tool discrimination does this required accuracy and precision demand?
3. What is the most reliable tool for this application?

Calibration Accurate and reliable measurement places a considerable amount of responsibility on a machinist. He or she is responsible for the conformity of his or her measuring tools to the appropriate standards. This is the process known as **calibration**. In a large industrial facility, all measuring tools are periodically cycled through the metrology laboratory, where they are calibrated against appropriate standards. Adjustments bring the tools into conformity to the standards. Only through this process can standardized measure within an individual plant or within an entire industrial nation be maintained. Most of the common measuring instruments provide a factory standard. Even though calibration cannot be carried out under laboratory conditions, the instruments should at least be checked periodically against available standards.

Variables in Measuring A machinist should be further aware that any measurement is **relative to the conditions under which it is taken.** A common expression often used around the machine shop is "the measurement is right on." There is, of course, little probability of obtaining a measurement that is truly exact. Each measurement has a certain degree of deviation from the theoretical exact size. This degree of error is dependent on many variables, including the measuring tool selected, the procedure used, the temperature of the part, the temperature of the room, the cleanliness of the room air, and the cleanliness of the part at the time of measurement. The deviation of a measurement from exact size is taken into consideration by the designer. Every measurement has a tolerance, meaning that the measurement is acceptable within a specific range. Tolerance can be quite small depending on design requirements. When this condition exists, reliable measurement becomes more difficult because it is more heavily influenced by the many variables present. Therefore, before a machinist makes any measurement, he or she should stop for a moment and consider the possible variables involved. He or she should then consider what might be done to control as many of these variables as possible.

If you understand these basic principles of dimensional metrology and you assume the proper responsibility in the selection, calibration, and application of measuring instruments, you will experience little difficulty in performing the many measurements encountered in the science of machine tools and machining practices.

TOOLS FOR DIMENSIONAL MEASUREMENT

There are several hundred measuring instruments available to a machinist. In this modern age there is a measuring instrument that can be applied to almost any conceivable measurement. Many instruments are simply variations and combinations of a few common precision measuring tools. As you begin your study of machine tool practices, you will be initially concerned with the use, care, and applications of the common measuring instruments found in the machine shop. These will be discussed in detail within this section.

In addition to these, a large variety of instruments are designed for many specialized uses. Some of these are rarely seen in the school or general-purpose machine shop. Others are intended for use in the tool room or metrology laboratory, where they are used in the calibration process. Your contact with these instruments will depend on the particular path you take while learning the trade.

Many measuring instruments have undergone modernization in recent years. Even though the function of these tools is basically the same, many have been redesigned and equipped with mechanical or electronic digital displays. These features make the instruments easier to read and improve accuracy. As a machinist, you must be skilled in the use of all the common measuring instruments. In addition, you should be familiar with the many important instruments used in production machining, inspection, and calibration. In the following pages many of these tools will be briefly described so that you may become familiar with the wide selection of measuring instruments available to the machinist.

Fixed Gages and Air Gages

Fixed Gages In production machining, where large numbers of duplicate parts are produced, it may be necessary to determine only if the part is within acceptable tolerance. Many types of fixed gages are used. The **adjustable limit snap gage** (Figure C-5) is used to check outside diameter. One anvil is set to the minimum limit of the tolerance to be measured. The other anvil is set to the maximum limit of the tolerance. If both anvils slip over the part, an undersize condition is indicated. If neither anvil slips over the part, an oversize condition is indicated. The gage is set initially to a known standard such as gage blocks.

Threaded products are often checked with fixed gages. The **thread plug gage** (Figure C-6) is used to check internal threads. The **thread ring gage** (Figure C-7) is used to check external threads. These are frequently called **go** and **no go** or **not go** gages. One end of the plug gage is at the low limit of the tolerance, and the other end is at the high limit of the tolerance. The thread gage functions in the same manner. Thread gages appear in many different forms (Figure C-8).

Fixed gages are also used to check internal and external tapers (Figure C-9). Plug gages are used for internal holes (Figure C-10). A ring gage is used for external diameters (Figure C-11).

Figure C-5 Adjustable limit snap gage.

Figure C-6 Thread plug gage.

Figure C-7 Thread ring gage.

Figure C-8 Fixed thread gages appear in many different forms (*Courtesy Vermont Gage*).

Figure C-9 Taper plug and taper ring gage (*Courtesy Prof. Frank Mueck, Cambrian College of Applied Arts and Technology Tool and Die Machining*).

Air Gages Air gages are also known as **pneumatic comparators.** Two types of air gages are used in comparison measuring applications. In the pressure-type air gage (Figure C-12), filtered air flows through a reference and a measuring channel. A sensitive differential pressure meter is connected across the channels (Figure C-13). The gage head is adjusted to a master setting gage. Air gage heads may be ring, snap (Figure C-14), or plug types (Figure C-15). Air flowing through the reference and the measuring channel is adjusted until the differential pressure meter reads zero with the setting master in place. A difference in workpiece size above or below the master size will cause more or less air to escape from the gage head. This, in turn, will change the pressure on the reference channel. The pressure change will be indicated on the differential pressure meter. The meter scale is graduated in suitable linear units. Thus workpiece size above or below the master can be directly determined.

In the column or flow-type air gage (Figure C-16), airflow from the gage head is indicated on a flowmeter or rotameter (Figure C-17). This type of air gage is also set to master gages. In the case of the plug gage shown, if the workpiece is oversize, more air will flow from the gage head. An undersize condition will permit less air to flow. Differences in flow are indicated on a suitably graduated flowmeter scale. Workpiece size deviation can be read directly.

Air gages have several advantages. The gage head does not touch the workpiece. Consequently, there is no wear on

Figure C-10 Using the cylindrical plug gage (*Courtesy Terra Community College*).

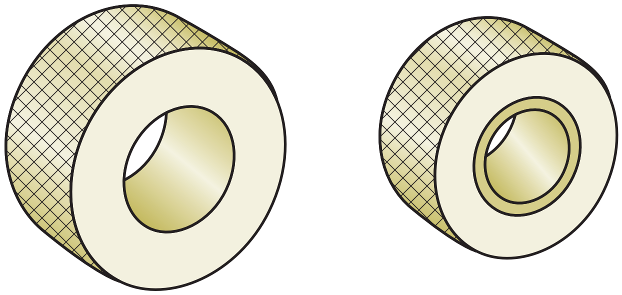


Figure C-11 Cylindrical ring gages.

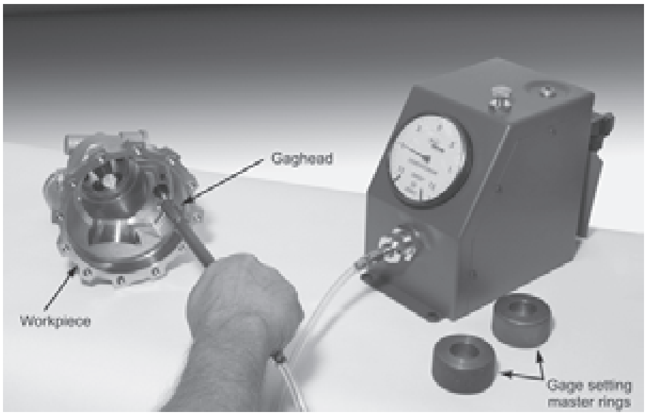


Figure C-12 Pressure-type air gage (*Courtesy Mahr Federal Inc.*).

the gage head and no damage to the finish of the workpiece. Variations in workpiece geometry that would be difficult to measure by mechanical means can be detected by air gaging (Figure C-18).

Mechanical Dial Measuring Instruments

Measuring instruments that show a measurement on a dial have become popular in recent years. Several common dial instruments are outgrowths from vernier instruments of the same type. Dial instruments have an advantage over their vernier counterparts in that they are easier to read. Dial measuring equipment is frequently found in the inspection department, where many types of measurements must be made quickly and accurately.

Dial Thickness Gage The **dial thickness gage** (Figure C-19) is used to measure the thickness of paper, leather, sheet metal, and rubber. Discrimination is .001 in.

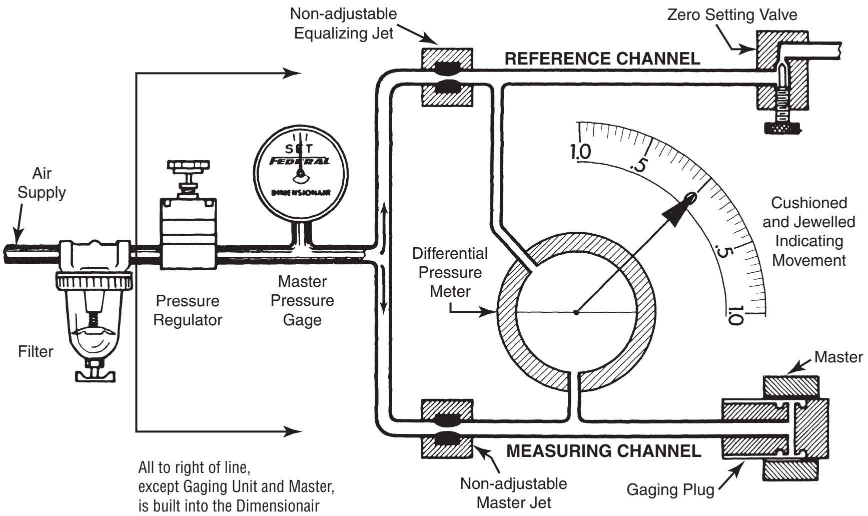


Figure C-13 Pressure-type air gage system (*Courtesy Mahr Federal Inc.*).

Figure C-14 Pressure-type air snap gage (*Courtesy Mahr Federal Inc.*).

Figure C-15 Air plug gage (*Courtesy Mahr Federal Inc.*).

Figure C-16 Column or flow-type air gage (*Besly Cutting Tools, Inc.*).

Dial Indicating Snap Gages **Dial indicating snap gages** (Figure C-20) are used for determining whether workpieces are within acceptable limits. They are first set to a master disc. Part size deviation is noted on the dial indicator.

Dial Bore Gage The **dial bore gage** (Figure C-21) uses a two-point measuring contact. This more accurately measures the true shape of a bore (Figure C-22). The dial bore gage is useful for checking engine block cylinders for size, taper, bellmouth, ovality, barrel shape, and hourglass shape (Figure C-23). Dial bore gages are set to a master ring and then compared to a bore diameter. Discrimination ranges from .001 to .0001 in.

Dial Indicating Expansion Plug Bore Gage The **indicating expansion plug gage** (Figure C-24) is used to measure the inside diameter of a hole or bore. This type of gage is built to check a range of dimensions. It can detect ovality, bellmouth, barrel shape, and taper. The expanding plug is retracted and the instrument inserted into the hole to be measured (Figure C-25).

Dial Indicating Thread Plug Gage The **indicating thread plug gage** (Figure C-26) is used to measure internal threads. This type of gage need not be screwed into the thread. The measuring anvils retract so that the gage may be inserted into a threaded hole.

Dial Indicating Screw Thread Snap Gage The dial **indicating screw thread snap gage** (Figure C-27) is used to measure an external thread. The instrument may be fitted with suitable anvils for measuring the major, minor, or pitch diameter of screw threads. Discrimination is .0005 or .00005 in., depending on the dial indicator used.

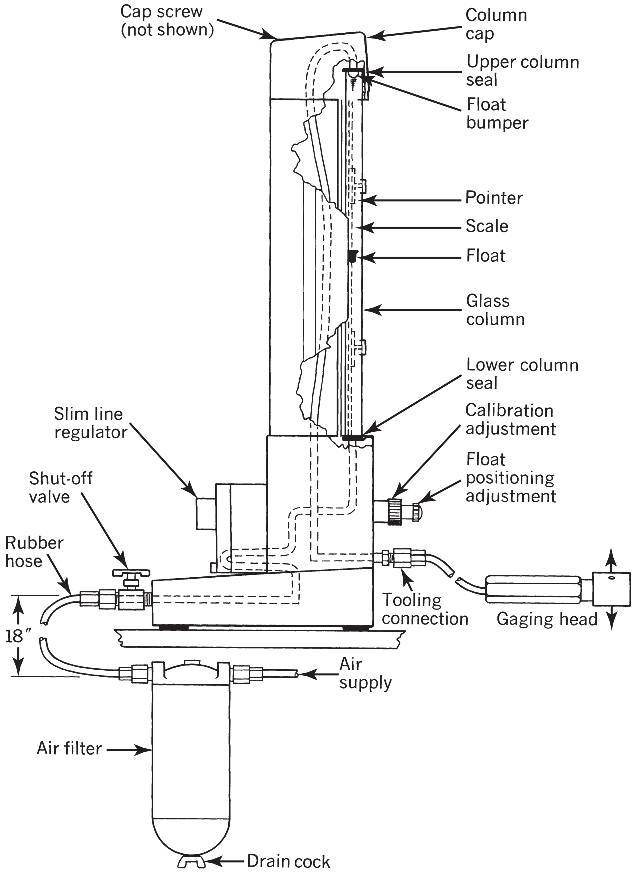


Figure C-17 Column-type air gage system (*Besly Cutting Tools, Inc.*).

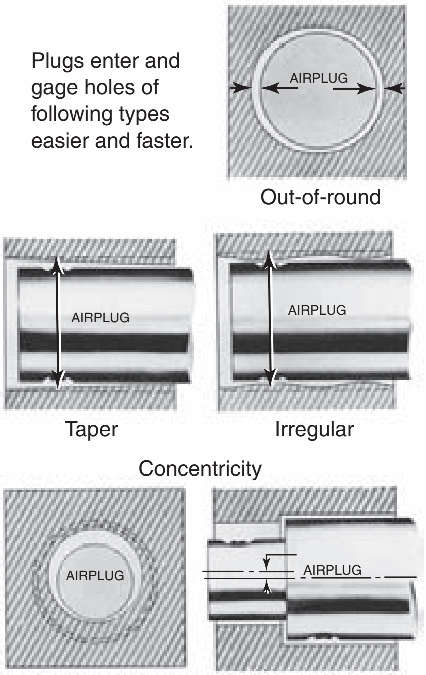


Figure C-18 Hole geometry detectable by air gaging (*Courtesy Mahr Federal Inc.*).

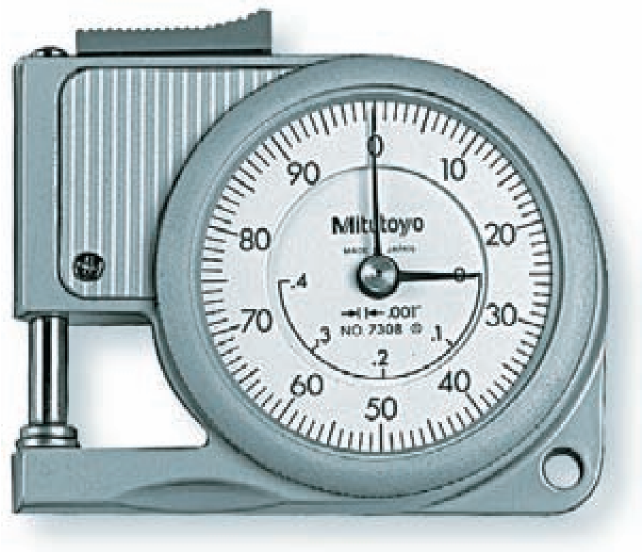


Figure C-19 Dial thickness gage (*Mitutoyo America Corp.*).

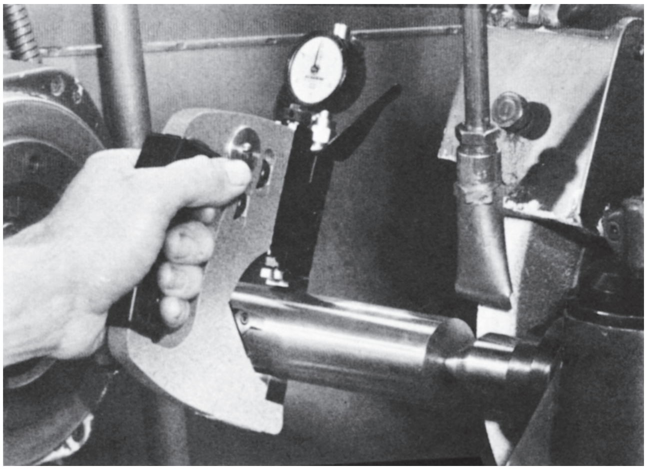


Figure C-20 Using the indicating snap gage (*Courtesy Mahr Federal Inc.*).

Dial Indicating Inprocess Grinding Gage Gages can be built into machining processes. The **indicating inprocess grinding gage** is used to measure the workpiece while it is still running in the machine tool (Figure C-28). The instrument swings down over the part to be measured (Figure C-29). The machine can remain running. These instruments are used in such applications as cylindrical grinding. Discrimination can be .0005 or .00005 in., depending on the dial indicator used. This instrument also has an electronic counterpart.

Mechanical Dial Indicating Travel Indicators **Mechanical dial indicators** can be used to indicate the travel of machine tool components. This is valuable to the machinist in controlling machine movement, which in turn controls the dimensions of the parts produced. Mechanical

Figure C-21 Dial bore gage (*Mitutoyo America Corp.*).

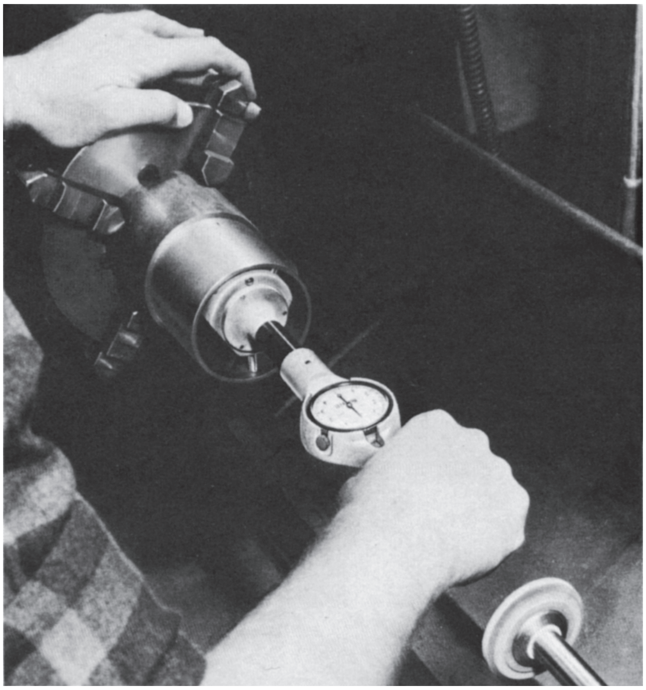


Figure C-22 Using the dial bore gage (*Courtesy The L.S. Starrett Co.*).

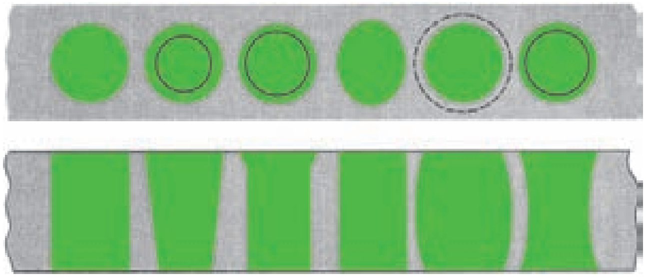


Figure C-23 Hole geometry detectable with the dial bore gage.

Figure C-24 Dial-indicating expansion plug bore gage (*Courtesy Mahr Federal Inc.*).

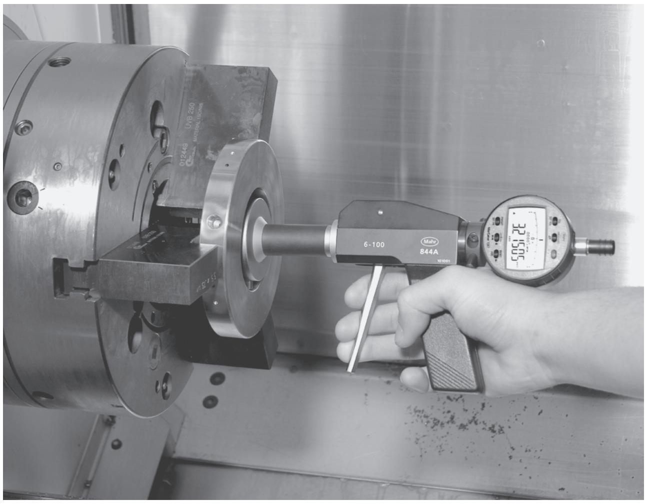


Figure C-25 Using the expansion plug bore gage (*Courtesy Mahr Federal Inc.*).

dial travel indicators are used in many applications, such as indicating table and saddle travel on a milling machine (Figure C-30). They may also indicate vertical travel of quills and spindles. Mechanical dial travel indicators are also useful

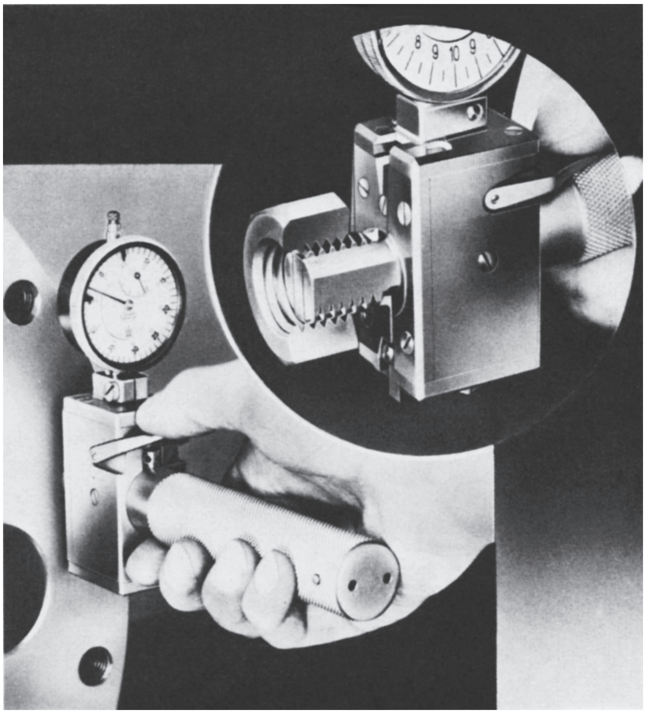


Figure C-26 Using the indicating thread plug gage (*Courtesy Mahr Federal Inc.*).

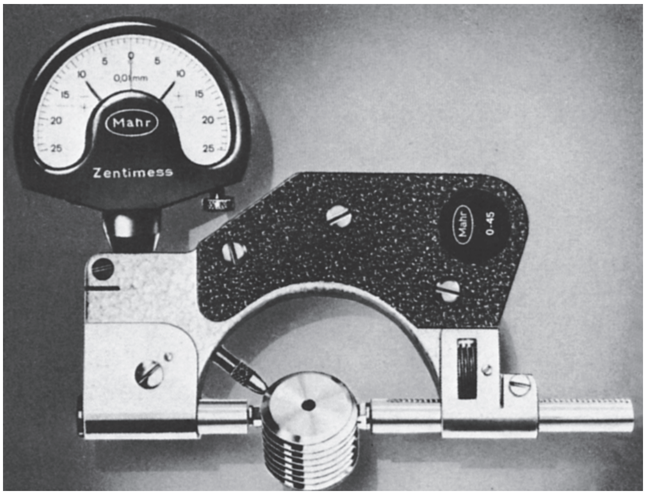


Figure C-27 Dial-indicating thread snap gage (*Courtesy Mahr Federal Inc.*).

for indicating travel in metric dimensions. Discrimination is .001 in., .005 in., and .01 mm.

Inspection and Calibration Through Mechanical Measurement

All measuring instruments must be checked periodically against accepted standards if the control that permits interchangeability of parts is to be maintained. Without control of measurement there could be no diverse mass production of parts that will later fit together to form the many products we now enjoy.

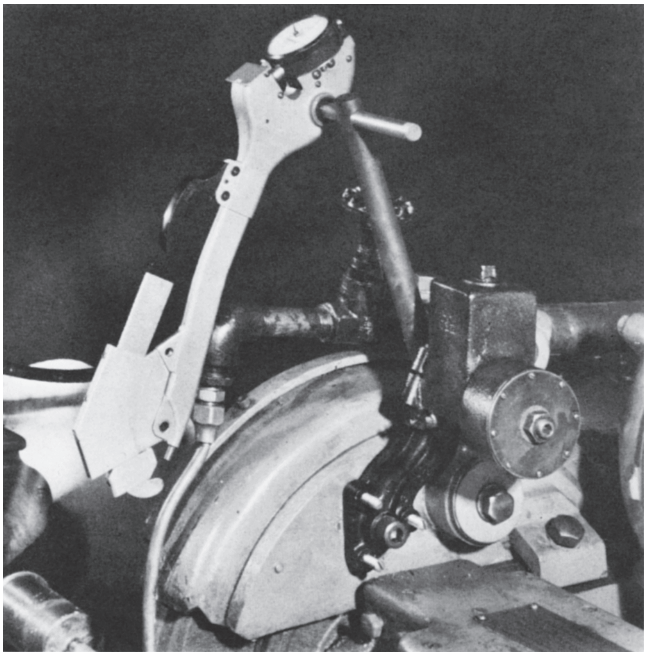


Figure C-28 Dial indicator inprocess grinding gage in retracted position (*Courtesy Mahr Federal Inc.*).

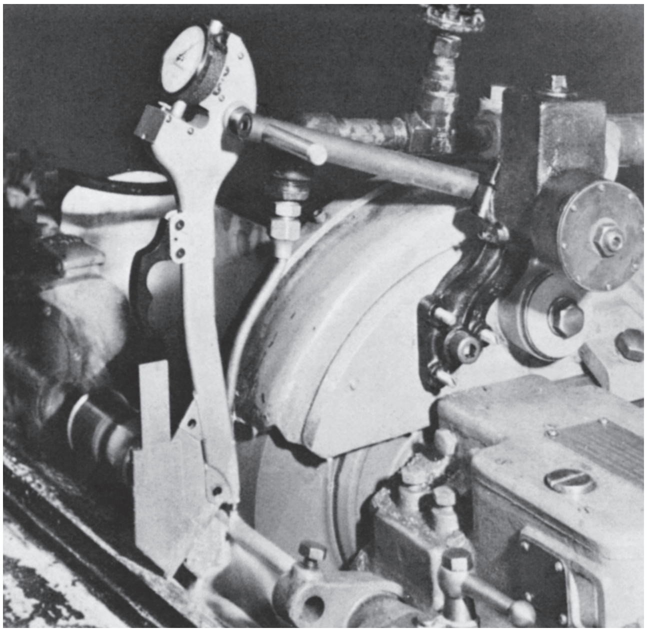


Figure C-29 Inprocess grinding gage measuring the workpiece (*Courtesy Mahr Federal Inc.*).

Parts produced on a machine tool must be inspected to determine if their size meets design requirements. Parts

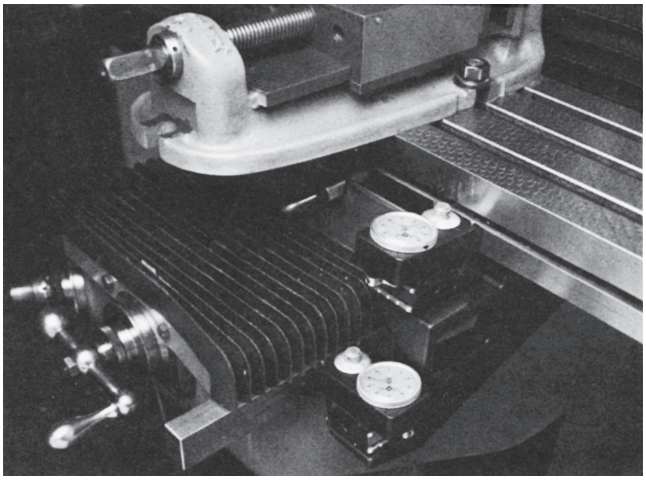


Figure C-30 Mechanical dial travel indicators installed on a milling machine (*Southwestern Industries, Inc.*).

produced out of tolerance can greatly increase the cost of production. These must be kept to a minimum, and this is the purpose of part inspection and calibration of measuring instruments.

Indicating Bench Micrometer The **indicating bench micrometer,** commonly called a **supermicrometer** (Figure C-31), is used to inspect tools, parts, and gages. This instrument has a discrimination of .00002 in. (20 millionths). This type of instrument also is available in an electronic digital model (Figure C-32).

Figure C-31 Using a micrometer to measure a workpiece.

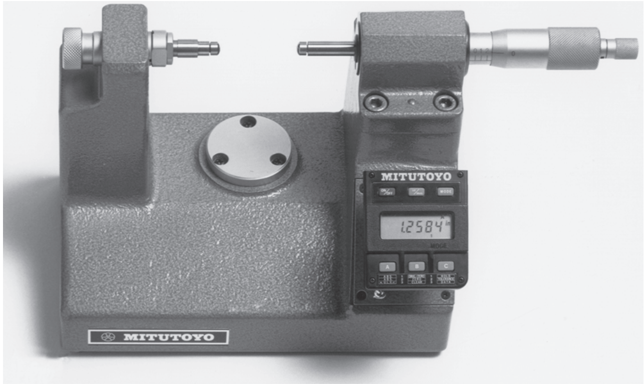


Figure C-32 Digital electronic bench micrometer (*Mitutoyo America Corp.*).

Figure C-33 Visual surface roughness comparator gage.

Surface Finish Visual Comparator Surface finish may be approximated by visual inspection using the **surface roughness gage** (Figure C-33). Samples of finishes produced by various machining operations are indicated on the gage. These can be visually compared to a machined surface to determine the approximate degree of surface finish.

Coordinate Measuring Machine The **coordinate measuring machine** (Figure C-34) is an extremely accurate instrument that can measure the workpiece in three dimensions. Coordinate measuring machines are useful for determining the location of a part feature relative to a reference plane, line, or point.

The electronic coordinate measuring machine is an indispensable tool for the inspector and gage laboratory. Many of these instruments are computer equipped, allowing calculations to be made relative to the measurements being taken. Computer printouts indicating graphs of measurement, as well as graphics illustrating the parts being measured, may be easily obtained. The computerized coordinate measuring machine is another example of the integration of digital readout electronics and computers into a precision mechanical system for modern high-precision measurement applications.

Measurement with Electronics

Remote Gaging Electronic technology has come into wide use in measurement. Electronic equipment can be designed with greater sensitivity than mechanical equipment. Thus, higher discrimination can be achieved.

Figure C-34 Three-axis coordinate measuring machine (*Mitutoyo America Corp.*).

Electronics can be applied in **remote gaging** applications (Figure C-35). In this application, there is no direct connection to the gaging. The operator is free to use the gaging anywhere on the machine tool. Data is transferred for collector and tool compensation.

Surface Finish Indicators Surface finish is critical on many parts such as bearing, gears, and hydraulic cylinders.

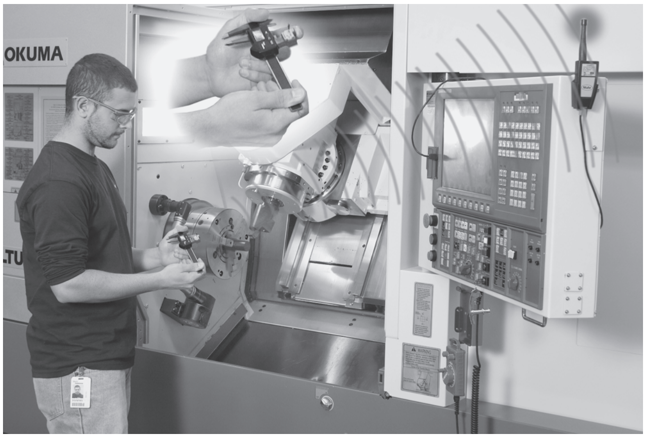


Figure C-35 Remote indicating gage (*Courtesy Mahr Federal Inc.*).

Figure C-36 Surface roughness instrument used to check a machined surface (*Mitutoyo America Corp.*).

Surface finish is a measure of **surface roughness** or **profile.** The measurement is in **microinches.** A **microinch** is **one millionth of an inch.** A surface finish indicator (Figure C-36) has a diamond-tipped stylus that activates an amplifier. The surface deviations are calculated and displayed on an LCD screen in various standard measures, such as **roughness average** (R_a).

Electronic Digital Travel Indicators **Electronic digital travel indicators** use a sensor attached to the machine tool. These systems will discriminate to .0001 in. and can be switched to read in metric dimensions. The travel of the machine component is indicated on a digital display (Figure C-37). These indicators are useful for the accurate positioning of

Figure C-37 Electronic digital travel indicator display.

machine tables on such tools as milling machines and jig borers (Figure C-38). A sensor on the machine tool detects movement of the machine components. The amount of travel is displayed on an electronic digital display.

Electronic Comparators **Electronic comparators** (Figure C-39) take advantage of the sensitivity of electronic equipment. They are used to make comparison measurements of parts and other measuring tools. For example, gage blocks may be calibrated using a suitable electronic comparator.

Measurement with Light

Toolmaker's Microscope The **toolmaker's microscope** (Figure C-40) is used to inspect parts, cutting tools, and measuring tools. The microscope has a stage that can be precisely rotated and moved in two perpendicular axes. The instrument may be equipped with an electronic accessory measuring system that discriminates to .0001 in. Thus stage movement can be recorded, permitting measurements of a workpiece to be made.

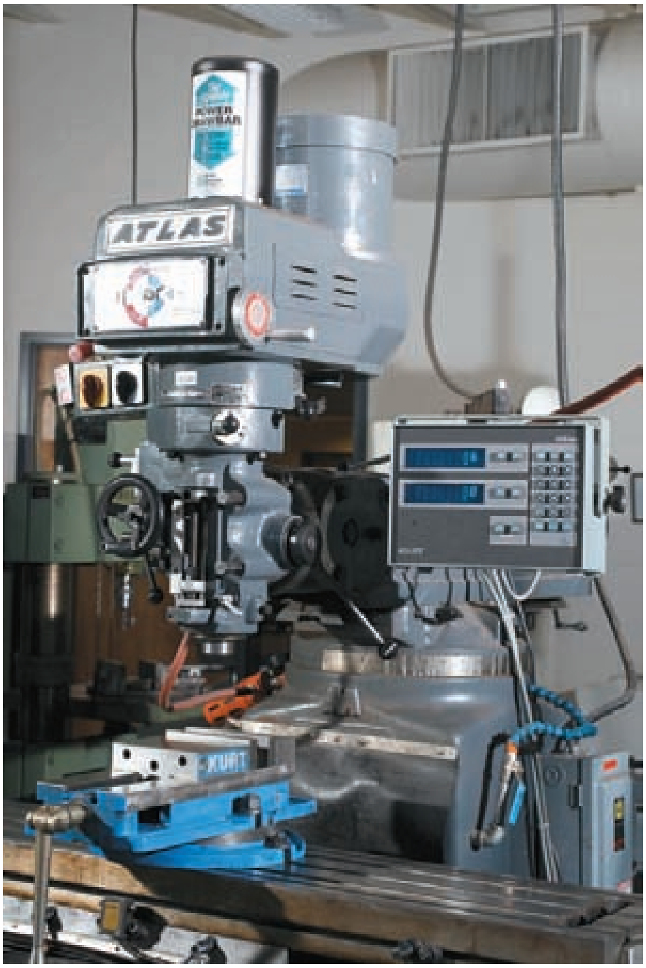


Figure C-38 Electronic digital travel indicator system installed on a vertical mill.

Figure C-39 Electronic comparator.

The **optical comparator** (Figure C-41) is used in the inspection of parts, cutting tools, and other measuring instruments. Optical comparators project a greatly magnified shadow of the object on a screen. The surface of the workpiece may also be illuminated. Shape patterns or graduated patterns can be placed on the screen and used to make measurements on the workpiece projection.

Optical flats are used in the inspection of other measuring instruments and for the measurement of flatness. They can be used, for example, to reveal the surface geometry

Figure C-40 Toolmaker's microscope with digital measuring heads (*Mitutoyo America Corp.*).

Figure C-41 Horizontal optical comparator (*Mitutoyo America Corp.*).

of a gage block or measuring faces of a micrometer (Figure C-42). Optical flats take advantage of the principles of light interferometry to make extremely small measurements in millionths of an inch.

Figure C-42 Using optical flats to check micrometer measuring faces (*Courtesy of DoALL Company*).

Autocollimators The **autocollimator** in Figure C-43 is being used to check the flatness of a surface plate. The mirror on the left is moved along the straightedge in small increments. Deviations from flatness are shown by angular changes of the mirror. This change is observed by the operator.

Alignment Telescope A machinist may accomplish alignment tasks by optical means. Optical alignment may be used on such applications as ship propeller shaft bearings. Portable machine tools such as boring bars may be positioned by optical alignment. The **dual micrometer alignment telescope** (Figure C-44) is a useful alignment instrument. The micrometers permit the deviation of the workpiece from the line of sight to be determined.

Laser Interferometer The term **laser** is an acronym for **light amplification by stimulated emission of radiation.** A laser light beam is a coherent beam. This means that each ray of light follows the same path. Thus, it does not disperse over long distances. This property makes the laser beam useful in many measurement and alignment applications. For example, the laser beam may be used to determine how straight a machine tool table travels (Figure C-45). Other uses include checking machine tool measuring systems (Figure C-46).

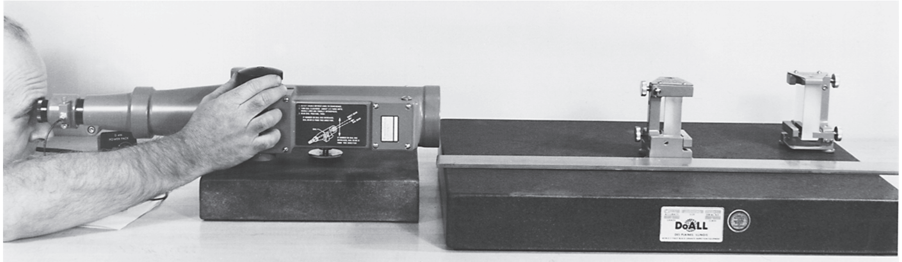


Figure C-43 Autocollimator checking a surface plate for flatness (*Courtesy of DoALL Company*).

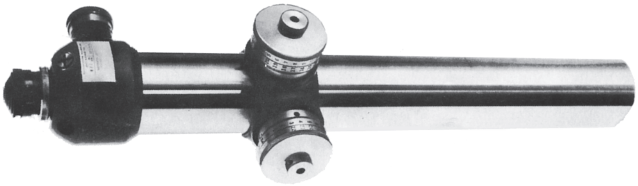


Figure C-44 Dual micrometer alignment telescope (*Courtesy of DoALL Company*).

Figure C-45 Laser interferometer being used for straightness determination (*Courtesy of Renishaw*).

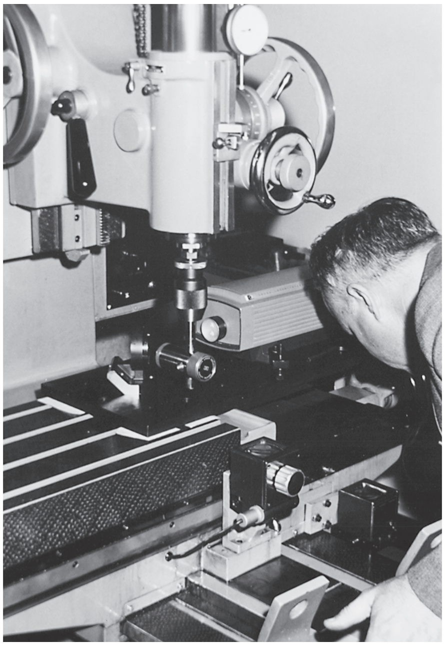


Figure C-46 Laser interferometer checking the measuring system on a jig boring machine (*Courtesy of Renishaw*).

INTERNET REFERENCES

Information on coordinate measuring machines and inspections systems:

http://www.aglient.com/metrology

http://www.starrett.com

http://www.prattandwhitney.com

UNIT ONE

Systems of Measurement

Throughout history there have been many systems of measurement. Prior to the era of national and international industrial operations, an individual was often responsible for the manufacture of a complete product. Since the same person made all the necessary parts and did the required assembly, he or she needed to conform only to his or her particular system of measurement. However, as machines replaced people and diversified mass production was established on a national and international basis, the need for standardization of measurement became readily apparent. Total standardization of measurement throughout the world has yet to be fully realized. Most measurements in the modern world do, however, conform to either the English (inch-pound-second) or the metric (meter-kilogram-second) system. Metric measurement is now predominant in most of the industrialized nations of the world. The English system is still used to a great extent in U.S. manufacturing. The importation of manufactured goods built to metric specifications has, in recent years, made the use of metric tools and measurements common in the United States.

Today's machinists must now begin to think in terms of metric measurement. During their careers they may come in contact with metric specifications. However, for the present they will be using inch measurement. Since you are primarily concerned with length measurement, this unit will review the basic length standards of both systems, examine mathematical and other methods of converting from system to system, and look at techniques by which a machine tool can be converted to work in metrics.

OBJECTIVES

After completing this unit, you should be able to:

- Identify common methods of measurement conversion.
- Convert inch dimensions to metric equivalents, and convert metric dimensions to inch equivalents.

ENGLISH SYSTEM OF MEASUREMENT

The English system of measurement uses the units inches, pounds, and seconds to represent the measurement of length, mass, and time, respectively. Since we are primarily concerned with the measurement of length in the machine shop, we will simply refer to the English system as the inch system. Most of us are thoroughly familiar with inch measurement.

Subdivisions and Multiples of the Inch

The following table shows the common subdivisions and multiples of the inch that are used by the machinist.

Common Subdivisions

.000001	millionth
.00001	hundred-thousandth
.0001	ten-thousandth
.001	thousandth
.01	hundredth
.1	tenth
1.00	Unit inch

Common Multiples and Other Subdivisions

12.00	1 foot
36.00	1 yard
$\frac{1}{128}$	.007810 (decimal equivalent)
$\frac{1}{64}$	.015625
$\frac{1}{32}$	.031250
$\frac{1}{20}$	.050000

$\frac{1}{16}$	.062500
$\frac{1}{8}$	.125000
$\frac{1}{4}$	.250000
$\frac{1}{2}$	.500000

Multiples of Feet

3 feet = 1 yard

5280 feet = 1 mile

Multiples of Yards

1760 yards = 1 mile

METRIC SYSTEM AND INTERNATIONAL SYSTEM OF UNITS—SI

The basic unit of length in the metric system is the *meter*. Originally the length of the meter was defined by a natural standard, specifically, a portion of the earth's circumference. Later, more convenient metal standards were constructed. In 1886, the metric system was legalized in the United States, but its use was not made mandatory. Since 1893, the yard has been defined in terms of the metric meter by the ratio

$$1 \text{ yard} = \frac{3600}{3937} \text{ meter}$$

Although the metric system had been in use for many years in many different countries, it still lacked complete standardization among its users. Therefore, an attempt was made to modernize and standardize the metric system. The result was the **Systéme International d'Unités,** known as **SI** or the **International Metric System.**

The basic unit of length in SI is the meter, or metre (in the common international spelling). The SI meter is defined by a physical standard that can be reproduced anywhere with unvarying accuracy:

1 meter = the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second

Probably the primary advantage of the metric system is that of convenience in computation. All subdivisions and multiples use 10 as a divisor or multiplier, as can be seen in the following table:

.000001	(one-millionth meter or micrometer)
.001	(one-thousandth meter or millimeter)
.01	(one-hundredth meter or centimeter)
.1	(one-tenth meter or decimeter)
1.00	*Unit meter*
10	(10 meters or 1 dekameter)
100	(100 meters or 1 hectometer)
1000	(1000 meters or 1 kilometer)
1,000,000	(1 million meters or 1 megameter)

METRIC SYSTEM EXAMPLES

1. One meter (m) = ________ millimeter (mm).
   Since a millimeter is 1/1000 part of a meter, there are 1000 mm in a meter.
2. 50 mm = ________ centimeters (cm).
   Since 1 cm = 10 mm, 50/10 = 5 cm in 50 mm.
3. Four kilometers (km) = ________ m.
   Since 1 km = 1000 m, then 4 km = 4000 m.
4. 582 mm = ________ cm.
   Since 10 mm = 1 cm, 582/10 = 58.2 cm.

CONVERSION BETWEEN SYSTEMS

Much of the difficulty with working in a two-system environment is experienced in converting from one system to the other. This can be of particular concern to the machinist, as he or she must exercise due caution in making conversions. Arithmetic errors can be easily made. Therefore, the use of a calculator is recommended.

Conversion Factors and Mathematical Conversion

Since the historical evolution of the inch and metric systems is quite different, there are no obvious relationships between length units of the two systems. You simply have to memorize the basic conversion factors. We know from the preceding discussion that the yard has been defined in terms of the meter. Knowing this relationship, you can mathematically derive any length unit in either system. However, the conversion factor

$$1 \text{ yard} = \frac{3600}{3937} \text{ meter}$$

is a less common factor for the machinist. A more common factor can be determined by the following:

$$1 \text{ yard} = \frac{3600}{3937} \text{ meter}$$

Therefore,

$$1 \text{ yard} = .91440 \text{ meter}$$
$$\left(\frac{3600}{3937} \text{ expressed in decimal form}\right)$$

Then

$$1\text{ inch} = \frac{1}{36}\text{ of }.91440\text{ meter}$$

So

$$\frac{.91440}{36} = .025400$$

We know that

$$1\text{ m} = 1000\text{ mm}$$

Therefore,

$$1\text{ in.} = .025400 \times 1000$$

or

$$\mathbf{1\text{ in.} = 25.4000\text{ mm}}$$

The conversion factor 1 in. = 25.4 mm is common and should be memorized. From the example shown it should be clear that in order to find inches knowing millimeters, you must divide inches by 25.4.

$$1000\text{ mm} = \_\_\_\_\_\text{ in.}$$

$$\frac{1000}{25.4} = 39.37\text{ in.}$$

To simplify the arithmetic, any conversion can always take the form of a multiplication problem.

EXAMPLE

Instead of 1000/25.4, multiply by the reciprocal of 25.4, which is 1/25.4 or .03937. Therefore,

$$1000 \times .03937 = 39.37\text{ in.}$$

EXAMPLES OF CONVERSIONS (INCH TO METRIC)

1. 17 in. = ________ cm. Knowing inches, to find centimeters multiply inches by 2.54: 2.54 × 17 in. = 43.18 cm.
2. .807 in. = ________ mm. Knowing inches, to find millimeters multiply inches by 25.4: 25.4 × .807 in. = 20.49 mm.

EXAMPLES OF CONVERSIONS (METRIC TO INCH)

1. .05 mm = ________ in. Knowing millimeters, to find inches multiply millimeters by .03937: .05 × .03937 = .00196 in.
2. 1.63 m = ________ in. Knowing meters, to find inches multiply meters by 39.37: 1.63 × 39.37 = 64.173 in.

Conversion Factors to Memorize

1 in. = 25.4 mm or 2.54 cm

1 mm = .03937 in.

Other Methods of Conversion

The conversion chart is a popular device for making conversions between systems. Conversion charts are readily available from many manufacturers. However, most conversion charts give equivalents for whole millimeters or standard fractional inches. If you must find an equivalent for a factor not on the chart, you must interpolate. In this instance, knowing the common conversion factors and determining the equivalent mathematically is more efficient.

Several electronic calculators designed to convert directly from one system to another are available. Of course, any calculator can and should be used to do a conversion problem. The direct converting calculator does not require that any conversion constant be remembered. These constants are permanently programmed into the calculator memory.

Converting Machine Tools

With the increase in metric measurement in industry, which predominantly uses the inch system, several devices have been developed that permit a machine tool to function in either system. These conversion devices eliminate the need to convert all dimensions prior to beginning a job.

Conversion equipment includes conversion dials (Figure C-47) that attach to lathe cross slide screws as well as milling machine saddle and table screws. The dials are equipped with gear ratios that permit a direct metric reading to appear on the dial.

Figure C-47 Inch/metric conversion dials for machine tools (*Sipco Machine Company*).

Figure C-48 Metric mechanical dial travel indicator (*Southwestern Industries, Inc.*).

Metric mechanical and electronic travel indicators can also be used. The mechanical dial travel indicator (Figure C-48) uses a roller that contacts a moving part of the machine tool. Travel of the machine component is indicated on the dial. This type of travel indicator discriminates to .01 mm. Whole millimeters are counted on the 1-mm counting wheel. Mechanical dial travel indicators are used in many applications such as reading the travel of a milling machine saddle and table (Figure C-49).

The digital electronic readout or DRO (Figure C-50) uses a sensor attached to the machine tool. Machine tool component travel is indicated on an electronic digital display. The equipment can be switched to read travel in inch or metric dimensions.

Metric conversion devices can be fitted to existing machine tools for a moderate expense. Many new machine tools, especially those built abroad, have dual system capability built into them.

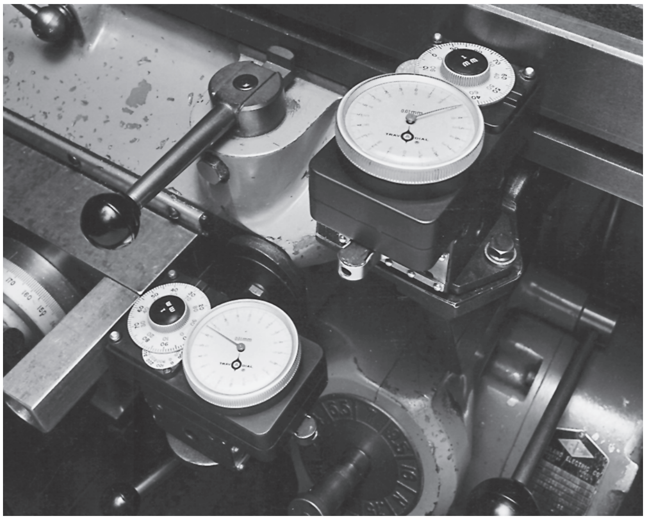


Figure C-49 Metric mechanical dial travel indicators reading milling machine saddle and table movement (*Southwestern Industries, Inc.*).

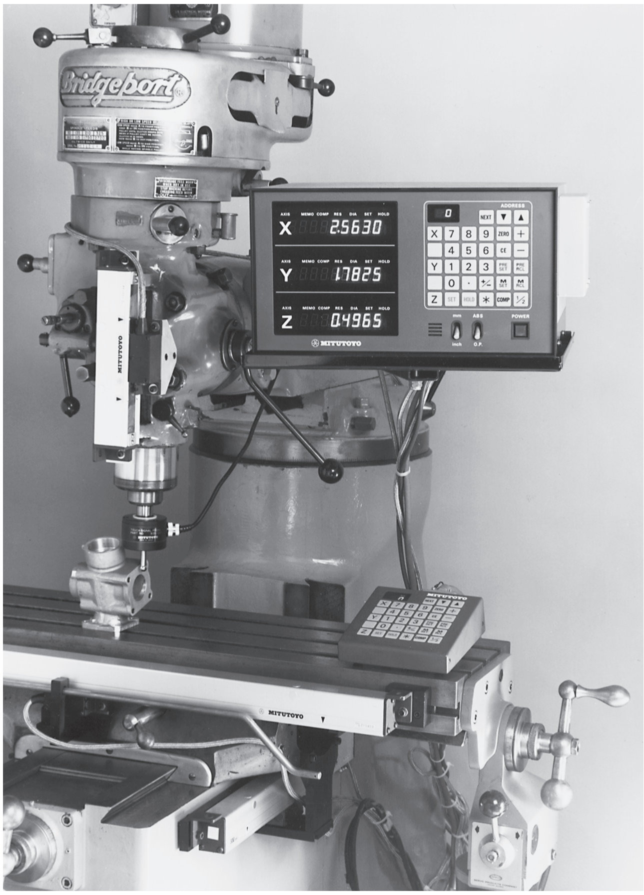


Figure C-50 High-discrimination digital electronic readout measurement system (DRO) installed on a milling machine (*Mitutoyo America Corp.*).

SELF-TEST

Perform the following conversions:

1. 35 mm = ________ in.
2. 125 in. = ________ mm
3. 6.273 in. = ________ mm
4. Express the tolerance ±.050 in metric terms to the nearest mm.
5. To find centimeters knowing millimeters, (multiply/divide) by 10.
6. Express the tolerance ±.02 mm in terms of inches to the nearest 1/10,000 in.
7. What is meant by *SI* ?
8. Describe methods by which conversions between metric and inch measurement systems may be accomplished.
9. How is the yard presently defined?
10. Can an inch machine tool be converted to work in metric units?

INTERNET REFERENCES

Information on systems of measurement:

http://www.webmath.com

http://ts.nist.gov/WeightsAndMeasures

UNIT TWO

Using Steel Rules

One of the most practical and common measuring tools available in the machining and inspection of parts is the steel rule. It is a tool that the machinist uses daily in different ways. It is important that anyone engaged in machining be able to select and use steel rules.

OBJECTIVES

After completing this unit, you should be able to:

- Identify various kinds of rules and their applications.
- Apply rules in typical machine shop measurements.

SCALES AND RULES

The terms **scale** and **rule** are often used interchangeably and often incorrectly. A rule is a linear measuring instrument whose graduations represent **real units** of lengths and their subdivisions. In contrast, a **scale** is graduated into **imaginary** units either smaller or larger than the real units they represent. This is done for convenience where proportional measurements are needed. For example, an architect uses a scale that has graduations representing feet and inches. However, the actual length of the graduations on the architect's scale are quite different from full-size dimensions.

DISCRIMINATION OF STEEL RULES

The general concept of **discrimination** was discussed in the introduction to this section. Discrimination refers to the extent to which a unit of length has been divided. If the smallest graduation on a specific rule is $\frac{1}{32}$ in., then the rule has a discrimination of, or discriminates to, $\frac{1}{32}$ in. Likewise, if the smallest graduation of the rule is $\frac{1}{64}$ in., then this rule discriminates to $\frac{1}{64}$ in.

The maximum discrimination of a steel rule is generally $\frac{1}{64}$ in., or in the case of the decimal inch rule, $\frac{1}{100}$ in. The metric rule has a discrimination of .05 mm. Remembering that a measuring tool should never be used beyond its discrimination, you should realize that the steel rule will not be reliable in trying to ascertain a measurement increment smaller than $\frac{1}{64}$ or $\frac{1}{100}$ in. If a specific measurement falls between the markings on the rule, only this can be said of this reading: It is more or less than the amount of the nearest mark. No further data as to how much more or less can be reliably determined. It is not recommended practice to attempt to read between the graduations on a steel rule with the intent of obtaining reliable readings.

RELIABILITY AND EXPECTATION OF ACCURACY IN STEEL RULES

For reliability, take great care if using the steel rule at its maximum discrimination. Remember that the markings on the rule occupy a certain width. A good-quality steel rule has engraved graduations. This means that the markings are actually cuts in the metal from which the rule is made. Of all types of graduations, engraved ones occupy the least width along the rule. Other rules, graduated by other processes, may have markings that occupy greater width. These rules are not necessarily any less accurate, but they may require more care in reading. Generally, the reliability of the rule will diminish as its maximum discrimination is approached. The smaller graduations are more difficult to see without the aid of a magnifier. Of particular importance is the point from which the measurement is taken. This **reference point** must be carefully aligned at the point where the length being measured begins.

From a practical standpoint, the steel rule finds widest application for measurements no smaller than $\frac{1}{32}$ in. on a fractional rule or $\frac{1}{50}$ in. on a decimal rule. This does not mean that the rule cannot measure to its maximum discrimination, because under the proper conditions it certainly can. However, at or near maximum discrimination, the time consumed to ensure reliable measurement is really not justified. You will be more productive if you make use of a type of measuring instrument with considerably finer discrimination for measurements below the nearest $\frac{1}{32}$ or $\frac{1}{50}$ in. It is good practice to take more than one reading when using a steel rule. After determining the desired measurement, apply the rule once again to see if the same result is obtained. This procedure increases the reliability factor.

TYPES OF RULES

Rules may be selected in many different shapes and sizes, depending on the need. The common **rigid steel rule** is 6 in. long, $\frac{3}{4}$ in. wide, and $\frac{3}{64}$ in. thick. It is engraved with No. 4 standard rule graduations. A No. 4 graduation consists of $\frac{1}{8}$- and $\frac{1}{16}$-in. divisions on one side (Figure C-51) and $\frac{1}{32}$ and $\frac{1}{64}$ in. divisions on the reverse side (Figure C-52). Other common graduations are summarized in the following table:

Graduation Number	Front Side	Back Side
3	32nds	10ths
	64ths	50ths
16	50ths	32nds
	100ths	64ths

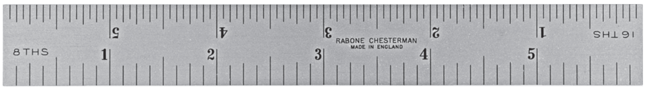


Figure C-51 Six-inch rigid steel rule (front side).

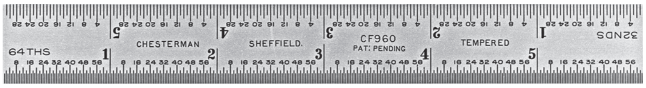


Figure C-52 Six-inch rigid steel rule (back side).

The No. 16 graduated rule is often found in the aircraft industry, where dimensions are specified in decimal fraction notations, which are based on 10 or a multiple of 10 divisions of an inch rather than 32 or 64 divisions, as found on common rules. Many rigid rules are 1 in. wide.

Another common rule is the **flexible type** (Figure C-53). This rule is 6 in. long, $\frac{1}{2}$ in. wide, and $\frac{1}{64}$ in. thick. Flexible rules are made from hardened and tempered spring steel. One advantage of a flexible rule is that it will bend, permitting measurements to be made in a space shorter than the length of the rule. Most flexible rules are 6 or 12 in. long.

The **narrow rule** (Figure C-54) is convenient when measuring in small openings, slots, or holes. Most narrow rules have only one set of graduations on each side. These can be No. 10, which is 32nds and 64ths, or No. 11, which is 64ths and 100ths.

The **standard hook rule** (Figure C-55) makes it possible to reach through an opening; the rule is hooked on the far side to measure a thickness or the depth of a slot (Figure C-56). When a workpiece has a chamfered edge, a hook rule will be advantageous over a common rule. If the hook is not loose or excessively worn, it will provide an easy-to-locate reference point.

The **short rule set** (Figure C-57) consists of a set of rules with a holder. Short rule sets have a range of $\frac{1}{4}$ or 1 in. They can be used to measure shoulders in holes or steps in slots, where space is extremely limited. The holder will attach to the rules at any angle, making these versatile tools.

The **slide caliper rule** (Figure C-58) is a versatile tool used to measure round bars, tubing, and other objects when it is difficult to measure at the ends and difficult to estimate the diameter with a rigid steel rule. The small slide caliper rule can also be used to measure internal dimensions from $\frac{1}{4}$ in. up to the capacity of the tool.

Figure C-53 Flexible steel rule (metric).

Figure C-54 Narrow rule (decimal inch).

Figure C-55 Standard hook rule.

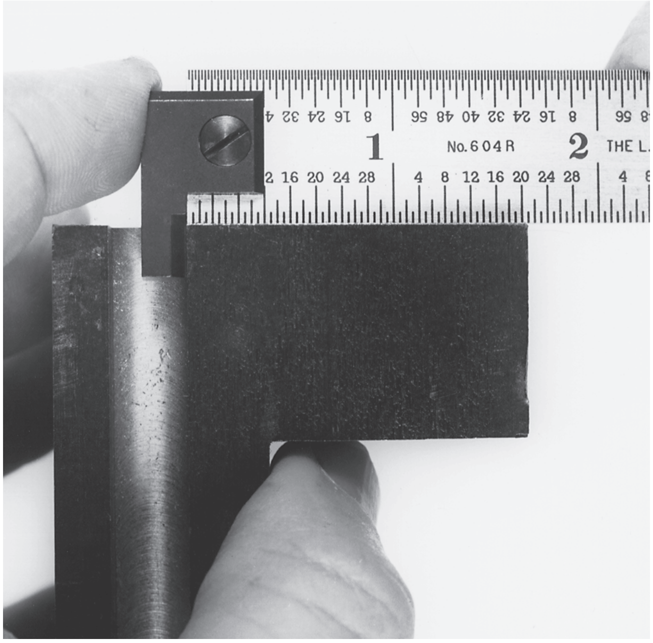


Figure C-56 Standard hook rule in use.

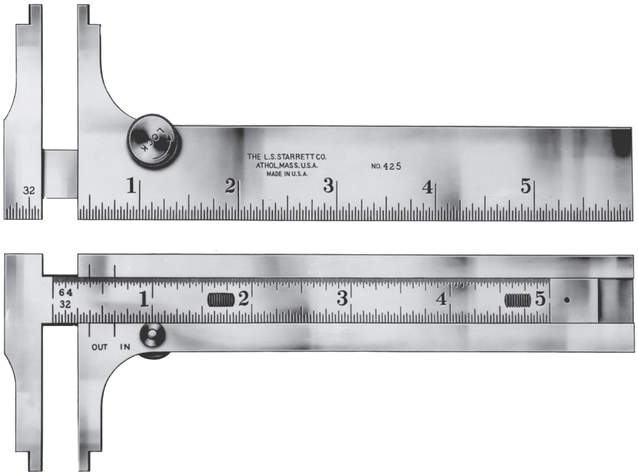


Figure C-58 Slide caliper rule (*Courtesy of The L.S. Starrett Co.*).

The **rule depth gage** (Figure C-59) consists of a slotted steel head in which a narrow rule slides. For depth measurements the head is held securely against the surface with the rule extended into the cavity or hole to be measured (Figure C-60).

Figure C-57 Short rule set with holder (*Courtesy of The L.S. Starrett Co*).

Figure C-59 Rule depth gage.

Figure C-60 Rule depth gage in use.

The locking nut is tightened and the rule depth gage can then be removed and the dimension determined.

CARE OF RULES

Rules are precision tools, and only those properly cared for will provide the kind of service they are designed to give. A rule should not be used as a screwdriver. Rules should be kept separate from hammers, wrenches, files, and other hand tools to protect them from possible damage. An occasional wiping of a rule with a lightly oiled shop towel will keep it clean and free from rust.

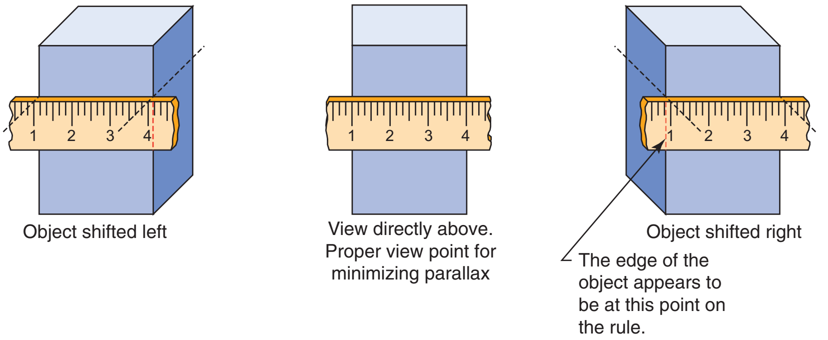
APPLYING STEEL RULES

When using a steel rule in close proximity to a machine tool, always keep safety in mind. Stop the machine before attempting to make any measurements of the workpiece. Attempting to measure with the machine running may cause the rule to be caught by a moving part. This may damage the rule, and worse, may result in serious injury to the operator.

One of the problems associated with the use of rules is that of **parallax error**. Parallax error results when the observer making the measurement is not in line with the workpiece and the rule. You may see the graduation either too far left or too far right of its real position (Figure C-61). Parallax error occurs when the rule is read from a point other than one directly above the point of measurement. The point of measurement is the point at which the measurement is read. It may or may not be the true reading of the size, depending on what location was used as the reference point on the rule. Parallax can be controlled by always observing the point of measurement from directly above. Furthermore, the graduations on a rule should be placed as close as possible to the surface being measured. In this regard, a thin rule is preferred to a thick rule.

Using a rule causes wear, usually on the ends. The outside inch markings on a worn rule are less than 1 in. from the end. This has to be considered when measurements are made. A reliable way to measure (Figure C-62) is to use the 1-in. mark on the rule as the reference point. In the figure, the measured point is at $2\frac{1}{32}$. Subtracting 1 in. results in a size of $1\frac{1}{32}$ for the part.

Round bars and tubing should be measured with the rule applied on the end of the tube or bar (Figure C-63). Select a reference point and set it carefully at a point on the circumference of the round part to be measured. Using the reference point as a pivot, move the rule back and forth slightly to find the largest distance across the diameter. When the largest distance is determined, read the measurement at that point.



When viewed from directly above, the rule gradations are exactly in line with the edge of the object being measured. However, when the object is shifted right or left of a point directly above the point of measurement, the alignment of the object edge and the rule graduations appears to no longer coincide.

Figure C-61 Parallax error.

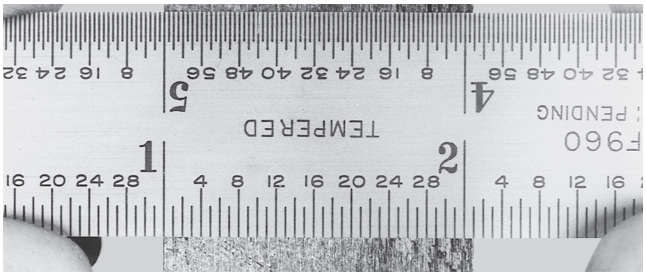


Figure C-62 Using the 1-in. mark as the reference point.

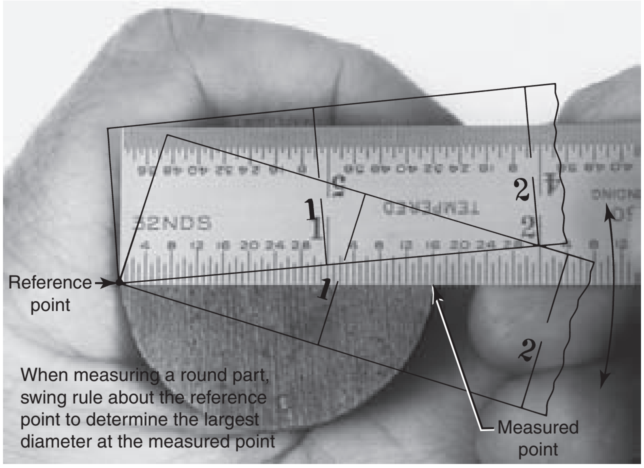


Figure C-63 Measuring round objects.

READING FRACTIONAL INCH RULES

Most dimensions are expressed in inches and fractions of inches. These dimensions are measured with fractional inch rules. The typical machinist's rule is broken down into 1-, $\frac{1}{2}$-, $\frac{1}{4}$-, $\frac{1}{8}$-, $\frac{1}{16}$-, $\frac{1}{32}$-, and $\frac{1}{64}$-in. graduations. To facilitate reading, the 1-, $\frac{1}{2}$-, $\frac{1}{4}$-, $\frac{1}{8}$-, and $\frac{1}{16}$-in. graduations appear on one side of the rule (Figure C-64). The reverse side of the rule has one edge graduated in $\frac{1}{32}$-in. increments and the other edge graduated in $\frac{1}{64}$-in. increments. On the $\frac{1}{32}$-in. side, every fourth mark is numbered, and on the $\frac{1}{64}$-in. side, every eighth mark is numbered (Figure C-65). This eliminates the need to count graduations from the nearest whole inch mark. On these rules, the length of the graduation line varies, with the 1-inch line being the longest, the $\frac{1}{2}$-in. line being next in length, and the $\frac{1}{4}$-, $\frac{1}{8}$-, and $\frac{1}{16}$-in. lines each being consecutively shorter. The difference in line lengths is an important aid in reading a rule. The smallest graduation on any edge of a rule is marked by small numbers on the end. Note that the words 8THS and 16THS appear at the ends of the rule. The numbers 32NDS and 64THS appear on the reverse side of the rule, thus indicating thirty-seconds and sixty-fourths of an inch.

EXAMPLES OF FRACTIONAL INCH READINGS

Figure C-66 Distance *A* falls on the third $\frac{1}{8}$-in. graduation. This reading would be $\frac{3}{8}$ in.

Distance *B* falls on the longest graduation between the end of the rule and the first full inch mark. The reading is $\frac{1}{2}$ in.

Distance *C* falls on the sixth $\frac{1}{8}$-in. graduation, making it $\frac{6}{8}$ or $\frac{3}{4}$ in.

Distance *D* falls at the fifth $\frac{1}{8}$-in. mark beyond the 2-in. graduation. The reading is $2\frac{5}{8}$ in.

Figure C-67 Distance *A* falls at the thirteenth $\frac{1}{16}$-in. mark, making the reading $\frac{13}{16}$ in.

Distance *B* falls at the first $\frac{1}{16}$-in. mark past the 1-in. graduation. The reading is $1\frac{1}{16}$ in.

Distance *C* falls at the seventh $\frac{1}{16}$-in. mark past the 1-in. graduation. The reading is $1\frac{7}{16}$ in.

Distance *D* falls at the third $\frac{1}{16}$-in. mark past the 2-in. graduation. The reading is $2\frac{3}{16}$ in.

Figure C-68 Distance *A* falls at the third $\frac{1}{32}$-in. mark. The reading is $\frac{3}{32}$ in.

Distance *B* falls at the ninth $\frac{1}{32}$-in. mark. The reading is $\frac{9}{32}$ in.

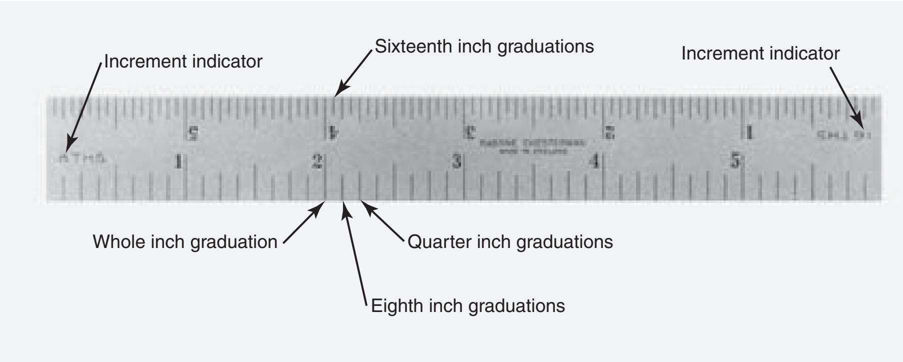
Distance *C* falls at the eleventh $\frac{1}{32}$-in. mark past the 1-in. graduation. The reading is $1\frac{11}{32}$ in.

Distance *D* falls at the fourth $\frac{1}{32}$-in. mark past the 2-in. graduation. The reading is $2\frac{4}{32}$ in., which reduced to lowest terms becomes $2\frac{1}{8}$ in.

Figure C-69 Distance *A* falls at the ninth $\frac{1}{64}$-in. mark, making the reading $\frac{9}{64}$ in.

Distance *B* falls at the fifty-seventh $\frac{1}{64}$-in. mark, making the reading $\frac{57}{64}$ in.

Figure C-64 Front-side graduations of the typical machinist's rule.



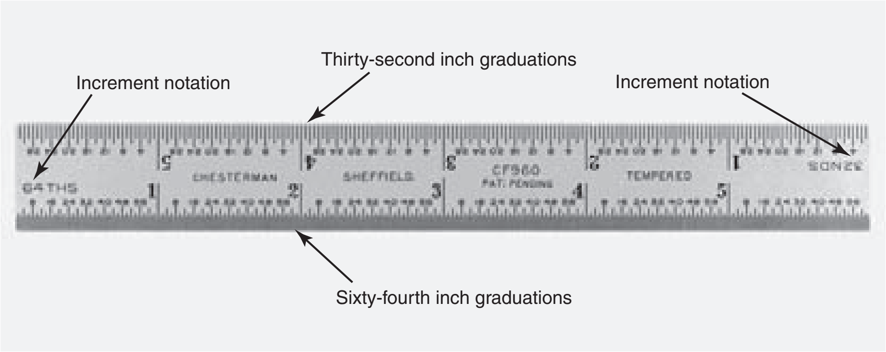


Figure C-65 Back-side graduations of the typical machinist's rule.

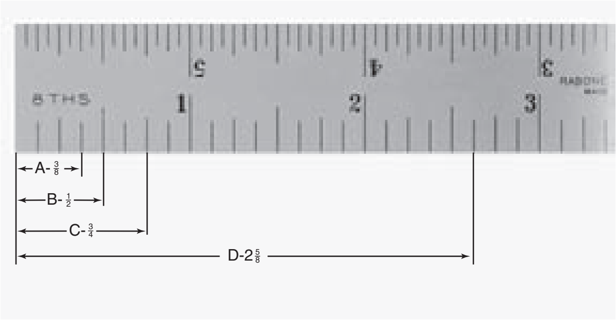


Figure C-66 Examples of readings on the $\frac{1}{8}$-in. discrimination edge.

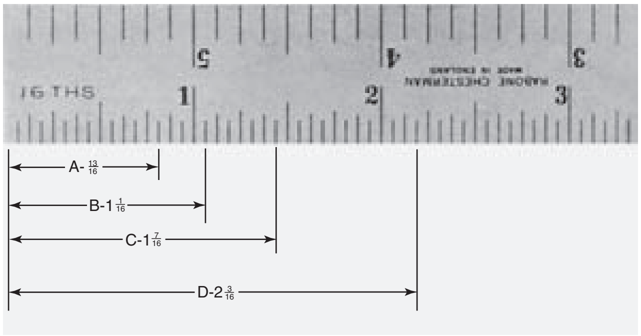


Figure C-67 Examples of readings on the $\frac{1}{16}$-in. discrimination edge.

Distance *C* falls at the thirty-third $\frac{1}{64}$-in. mark past the 1-in. graduation. The reading is 1$\frac{33}{64}$ in.

Distance *D* falls at the first $\frac{1}{64}$-in. mark past the 2-in. graduation, making the reading 2$\frac{1}{64}$ in.

READING DECIMAL INCH RULES

Many dimensions in the auto, aircraft, and missile industries are specified in **decimal notation,** which refers to the division of the inch into 10 parts or a multiple of 10 parts, such as 50 or 100 parts. In this case, a **decimal rule** is used. Decimal inch dimensions are specified and read as thousandths of an inch. Decimal rules, however, do not discriminate to the individual thousandth because the width of an engraved or etched division on the rule is approximately .003 in. (3 thousandths of an inch). Decimal rules are commonly graduated in increments of $\frac{1}{10}$, $\frac{1}{50}$, or $\frac{1}{100}$ in.

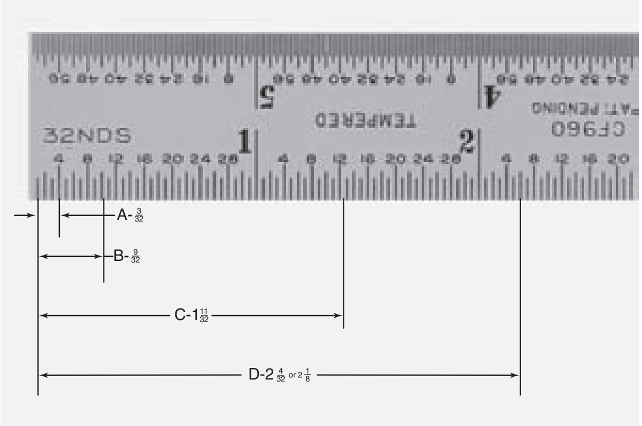


Figure C-68 Examples of readings on the $\frac{1}{32}$-in. discrimination edge.

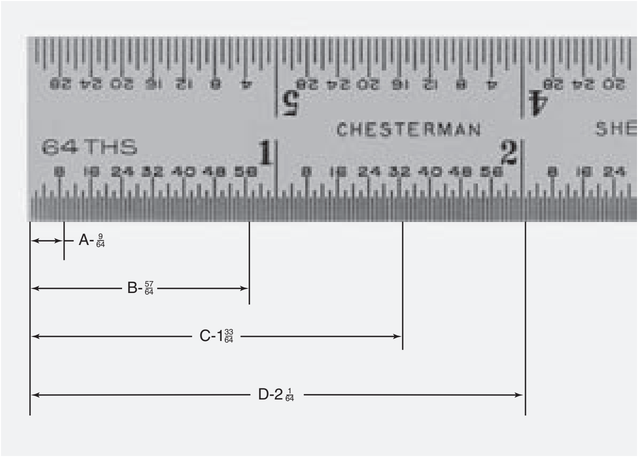


Figure C-69 Examples of readings on the $\frac{1}{64}$-in. discrimination edge.

A typical decimal rule may have $\frac{1}{50}$-in. divisions on the top edge and $\frac{1}{100}$-in. divisions on the bottom edge (Figure C-70). The inch is divided into 10 equal parts, making each numbered division $\frac{1}{10}$ in. or .100 in. (100 thousandths

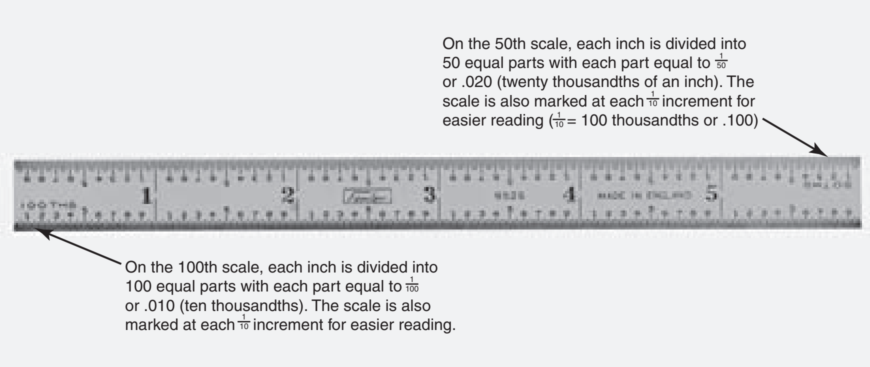


Figure C-70 Six-inch decimal rule.

On the 50th scale, each inch is divided into 50 equal parts with each part equal to $\frac{1}{50}$ or .020 (twenty thousandths of an inch). The scale is also marked at each $\frac{1}{10}$ increment for easier reading ($\frac{1}{10}$ = 100 thousandths or .100)

On the 100th scale, each inch is divided into 100 equal parts with each part equal to $\frac{1}{100}$ or .010 (ten thousandths). The scale is also marked at each $\frac{1}{10}$ increment for easier reading.

of an inch). On the top scale each $\frac{1}{10}$ increment is further subdivided into five equal parts, which makes the value of each of these divisions .020 in. (20 thousandths of an inch).

EXAMPLES OF DECIMAL INCH READINGS

Figure C-71 Distance *A* falls on the first marked graduation. The reading is $\frac{1}{10}$ or .100 in. This can also be read on the 50th-in. scale, as seen in the figure.

Distance *B* can be read only on the 100th-in. scale, as it falls at the seventh graduation beyond the .10 in. mark. The reading is .100 in. plus .070 in., or .170 in. This distance cannot be read on the 50th-in. scale because discrimination of the 50th-in. scale is not sufficient.

Distance *C* falls at the second mark beyond the .400-in. line. This reading is .400 in. plus .020 in., or .420 in. Since .020 in. is equal to $\frac{1}{50}$ in., this can also be read on the 50th-in. scale, as shown in the figure.

Distance *D* falls at the sixth increment beyond the .400-in. line. The reading is .400 in. plus .060 in., or .460 in. This can also be read on the 50th-in. scale, as seen in the figure.

Distance *E* falls at the sixth division beyond the .700-in. mark. The reading is .700 in. plus .040 in., or .740 in. This can also be read on the 50th-in. scale.

Distance *F* falls at the eighth mark beyond the .700-in. line. The reading is .700 in. plus .080 in., or .780 in. This cannot be read on the 50th-in. scale.

Distance *G* falls at the .100 graduation on top and at the .900 graduation on the bottom. The reading is .900, or $\frac{9}{10}$ in.

Distance *H* falls two marks past the first full inch mark. The reading is 1.00 in. plus .020 in., or 1.020 in.

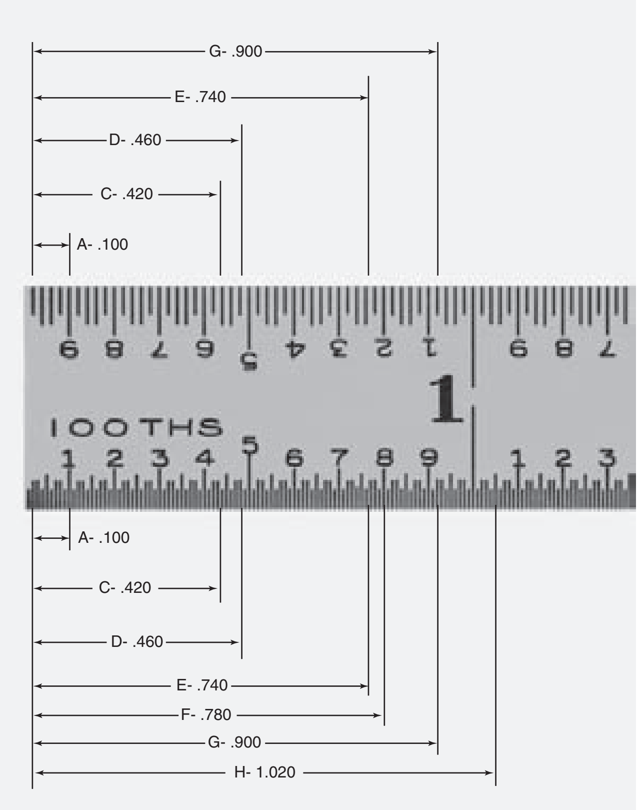


Figure C-71 Examples of decimal rule readings.

READING METRIC RULES

Many products are made in metric dimensions requiring a machinist to use a **metric rule.** The typical metric rule has millimeter (mm) and half-millimeter graduations (Figure C-72).

EXAMPLES OF READING METRIC RULES

Figure C-73 Distance *A* falls at the fifty-third graduation on the mm scale. The reading is 53 mm.

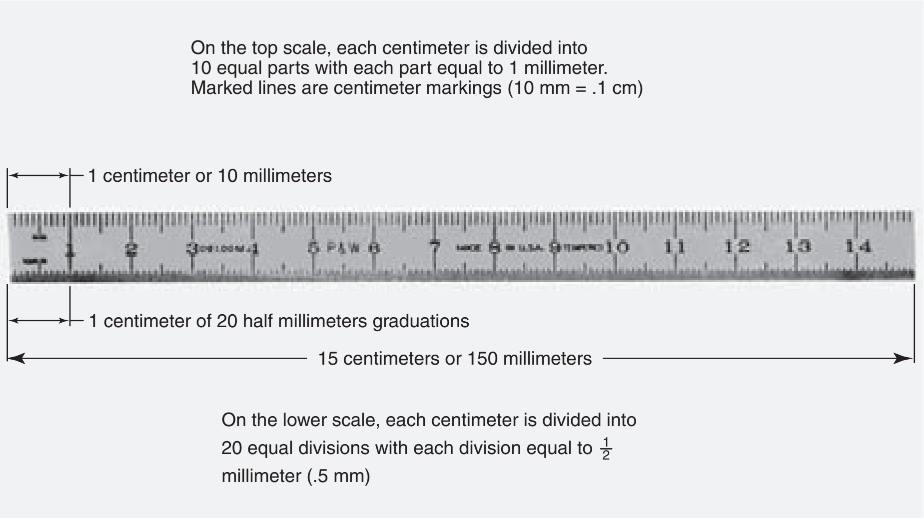
Distance *B* falls at the twenty-second graduation on the mm scale. The reading is 22 mm.

Distance *C* falls at the sixth graduation on the mm scale. The reading is 6 mm.

Distance *D* falls at the seventeenth $\frac{1}{2}$-mm mark. The reading is 8 mm plus an additional $\frac{1}{2}$ mm, giving a total of 8.5 mm.

Distance *E* falls $\frac{1}{2}$ mm beyond the 3-cm graduation. Since 3 cm is equal to 30 mm, the reading is 30.5 mm.

Distance *F* falls $\frac{1}{2}$ mm beyond the 51-mm graduation. The reading is 51.5 mm. In machine design, all dimensions are specified in mm. Hence 1.5 meters (m) would be 1500 mm.


On the top scale, each centimeter is divided into 10 equal parts with each part equal to 1 millimeter. Marked lines are centimeter markings (10 mm = .1 cm)

On the lower scale, each centimeter is divided into 20 equal divisions with each division equal to $\frac{1}{2}$ millimeter (.5 mm)

Figure C-72 150-mm metric rule.

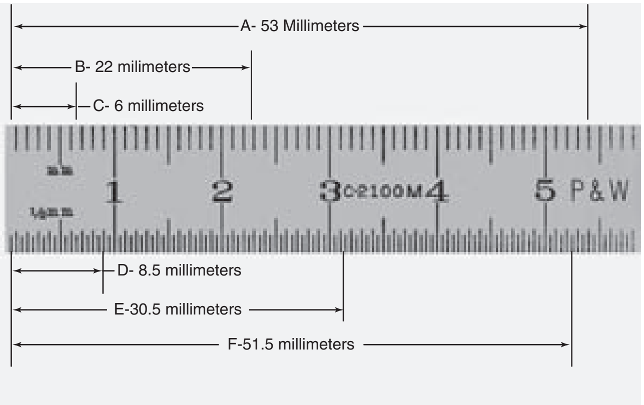


Figure C-73 Examples of metric rule readings.

SELF-TEST: READING INCH RULES

Read and record the dimensions indicated by the letters *A* to *H* in Figures C-74*a* to C-74*d*.

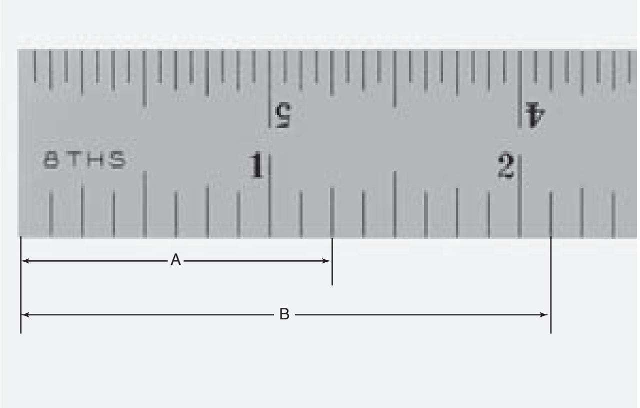


Figure C-74*a*

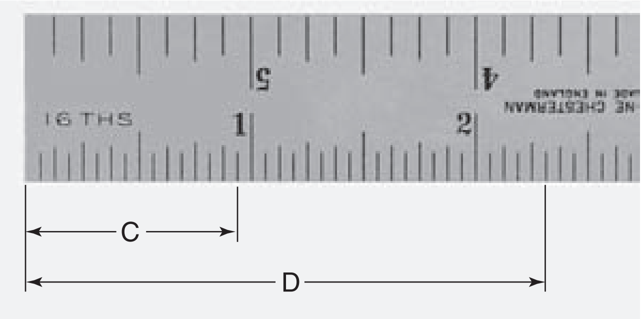


Figure C-74*b*

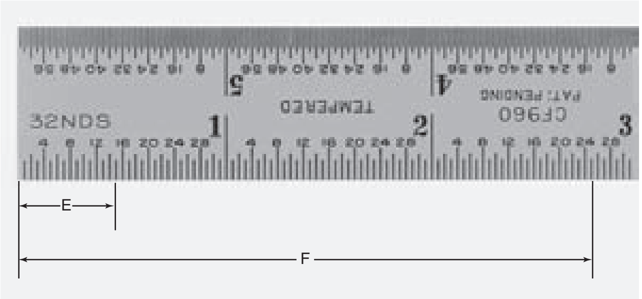


Figure C-74*c*

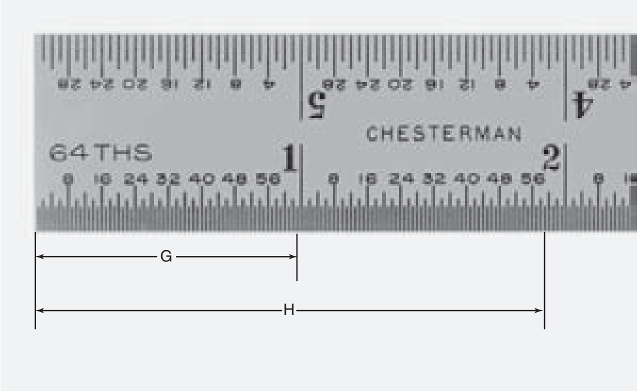


Figure C-74*d*

SELF-TEST: READING DECIMAL RULES

Read and record the dimensions indicated by the letters *A* to *E* in Figure C-75.

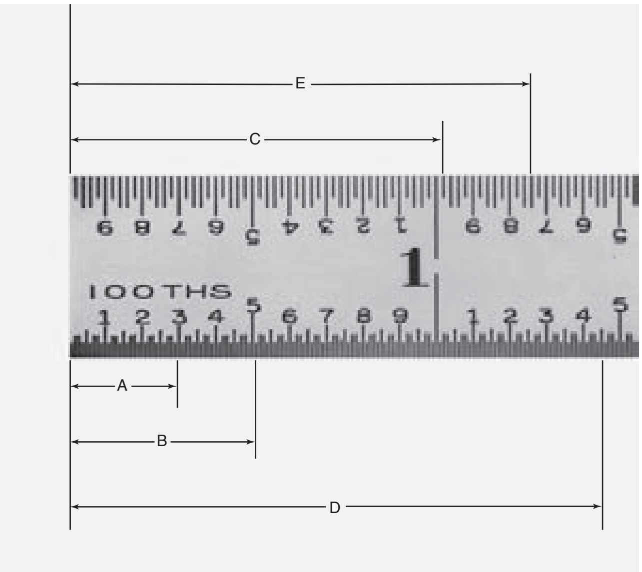


Figure C-75 Decimal inch rule.

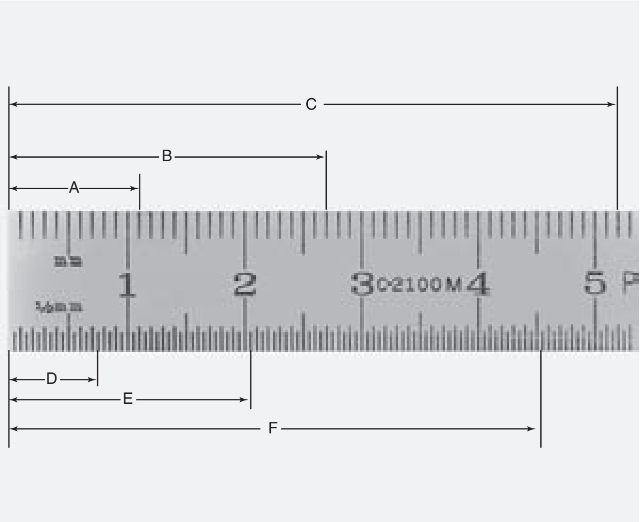


Figure C-76

SELF-TEST: READING METRIC RULES

Read and record the dimensions indicated by the letters *A* to *F* in Figure C-76.

INTERNET REFERENCE

Information on steel rules:

http://www.fine-tools.com/mass.htm

UNIT THREE

Using Vernier, Dial, and Digital Instruments for Direct Measurements

The inspection and measurement of machined parts require various kinds of measuring tools. Often, the discrimination of a rule is sufficient, but in many cases the discrimination of a rule with a vernier scale is required. This unit explains the types, use, and applications of common vernier dial and digital instruments.

OBJECTIVES

After completing this unit, you should be able to:

- Measure and record dimensions to an accuracy of plus or minus .001 in. with a vernier caliper.
- Measure and record dimensions to an accuracy of plus or minus .02 mm using a metric vernier caliper.
- Measure and record dimensions using a vernier depth gage.

USE OF THE VERNIER

For many years the vernier has been used to divide the units in which a measuring tool measures into smaller increments, permitting high discrimination measurement. Although the vernier is highly reliable and accurate, the nature of its function makes it somewhat difficult to read, thus requiring more time and skill on the part of the machinist. Modern precision manufacturing techniques and the wide application of digital microelectronics developed in recent years have yielded many types of high-discrimination measuring instruments that demonstrate both ease of use and excellent reliability. Thus the use of the mechanical vernier has declined. As digital electronics replace more mechanical measurement, use of the vernier may in time disappear completely. However, vernier measuring equipment is still much used in both school and industrial shops, and it is likely that vernier applications will be around for some time to come. The theory and applications of the vernier as a device for subdividing increments of measurement are discussed in this unit.

PRINCIPLE OF THE VERNIER

The principle of the **vernier** may be used to increase the discrimination of all graduated scale measuring tools used by a machinist. A vernier system consists of a **main scale** and a **vernier scale**. The vernier scale is placed adjacent to the main scale so that graduations on both scales can be observed together. The spacing of the vernier scale graduations is shorter than the spacing of the main scale graduations. For example, consider a main scale divided as shown (Figure C-77*a*). It is desired to further subdivide each main scale division into 10 parts with the use of a vernier. The spacing of each vernier scale division is made $\frac{1}{10}$ of a main scale division shorter than the spacing of a main scale division. This may sound confusing, but think of it as 10 vernier scale divisions corresponding to 9 main scale divisions (Figure C-77*a*). The vernier now permits the main scale to discriminate to $\frac{1}{10}$ of its major divisions. Therefore, $\frac{1}{10}$ is known as the **least count** of the vernier.

The vernier functions in the following manner. Assume that the zero line on the vernier scale is placed as shown (Figure C-77*b*). The reading on the main scale is 2 plus a fraction of a division. You want to know the amount of the fraction over 2 to the nearest tenth, or least count, of the vernier. As you inspect the alignment of the vernier scale and the main scale lines, you note that they move closer together until one line on the vernier scale **coincides** with a line on the main scale. This is the **coincident line** of the vernier and indicates the fraction in tenths that must be added to the main scale reading. The vernier is coincident at the sixth line. Since the least count of the vernier is $\frac{1}{10}$, the zero vernier line is $\frac{6}{10}$ past 2 on the main scale. Therefore, the main scale reading is 2.6 (Figure C-77*b*).

DISCRIMINATION AND APPLICATIONS OF VERNIER INSTRUMENTS

Vernier instruments used for linear measure in the inch system discriminate to .001 in. ($\frac{1}{1000}$). Metric verniers generally discriminate to $\frac{1}{50}$ mm.

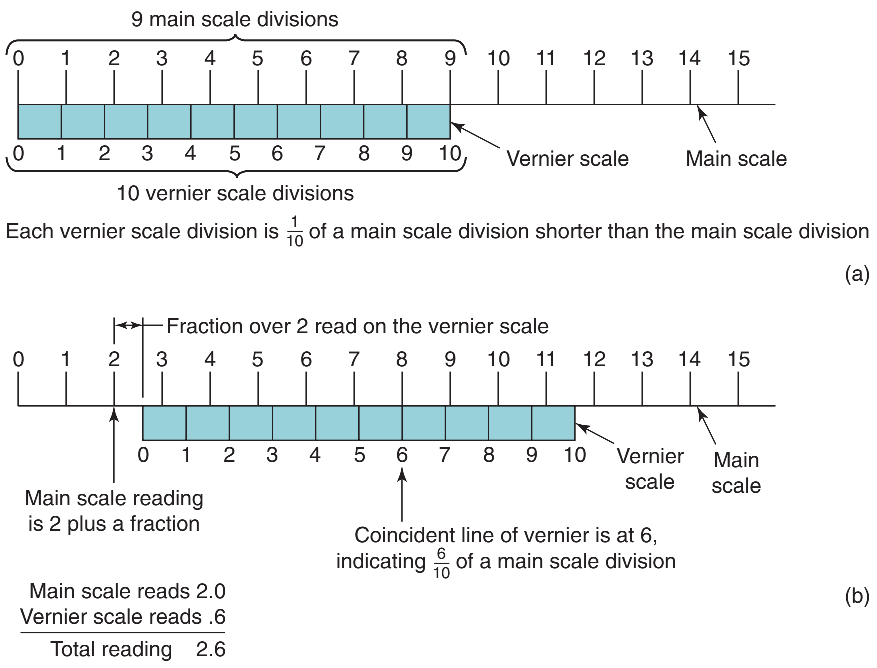


Figure C-77 Principle of the vernier.

The most common vernier instruments include several styles of **calipers.** The common vernier caliper is used for outside and inside linear measurement. Another style of vernier caliper has the capability of depth measurement in addition to outside and inside capacity. The vernier also appears on a variety of depth gages.

Beyond its most common applications, the vernier also appears on a height gage, an extremely important layout tool for a machinist. The vernier is also used on the gear tooth caliper, a special vernier caliper used in gear measurement. Because the principle of the vernier can be used to subdivide a unit of angular measure as well as linear measure, it appears on various types of protractors used for angular measurement.

RELIABILITY AND EXPECTATION OF ACCURACY IN VERNIER INSTRUMENTS

Reliability in vernier calipers and depths gages is highly dependent on proper use of the tool. The simple fact that the caliper or depth gage has increased discrimination over a rule does not necessarily provide increased reliability. The improved degree of discrimination in vernier instruments requires more than the mere visual alignment of a rule graduation against the edge of the object to be measured. The zero reference point of a vernier caliper is the positively placed contact of the solid saw with the part to be measured. On the depth gage, the base is the zero reference point. Positive contact of the zero reference is an important consideration in vernier reliability.

The vernier scale must be read carefully if a reliable measurement is to be determined. On many vernier instruments the vernier scale should be read with the aid of a magnifier. Without this aid, the coincident line of the vernier is difficult to determine. Therefore, the reliability of the vernier readings can be in question. The typical vernier caliper has narrow jaws and thus must be carefully aligned with the axis of measurement. On the plain slide vernier caliper, no provision is made for the “feel” of the measuring pressure. Some calipers and the depth gage are equipped with a screw-thread fine adjustment that gives them a slight advantage in determining the pressure applied during the measurement.

Generally, the overall reliability of vernier instruments for measurement at maximum discrimination of .001 is fairly low. The vernier should never be used in an attempt to discriminate below .001. The instrument lacks that capability. Vernier instruments are a popular tool on the inspection bench, and they can serve well for measurement in the range of plus or minus .005 in. With proper use and an understanding of the limitations of a vernier instrument, this tool can be a valuable addition to the many measuring tools available to you.

VERNIER CALIPERS

With a rule, measurements can be made to the nearest $\frac{1}{64}$ or $\frac{1}{100}$ in., but often this is not sufficiently accurate. A measuring tool based on a rule but with much greater discrimination is the **vernier caliper.** Vernier calipers have a discrimination of .001 in. The **beam** or **bar** is engraved with the **main scale.** This is also called the **true scale,** as the inch markings are exactly 1 in. apart. The beam and the solid jaw are square, or at 90 degrees to each other.

The movable jaw contains the **vernier scale.** This scale is located on the sliding jaw of a vernier caliper or is part of the base on the vernier depth gage. The function of the

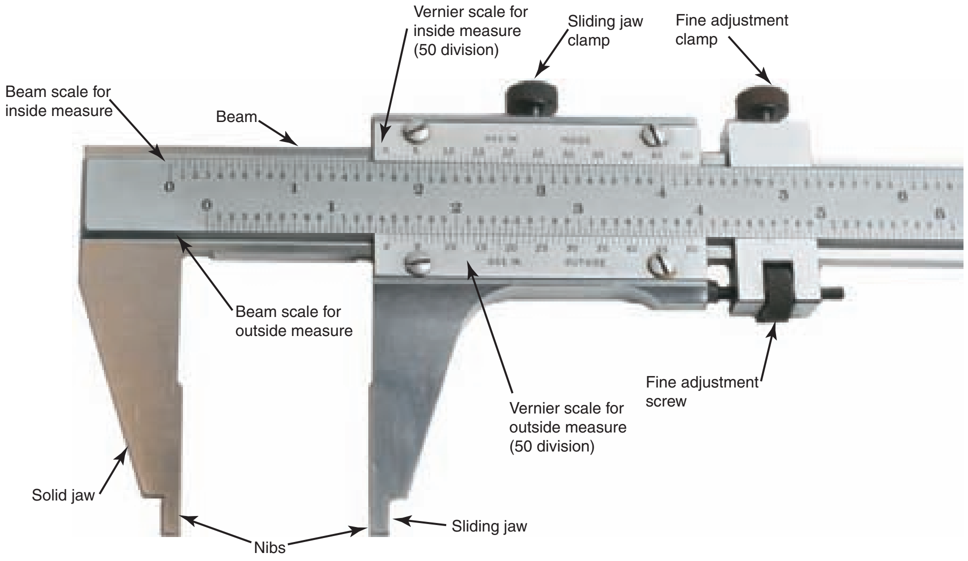


Figure C-78 Typical inside-outside 50-division vernier caliper.

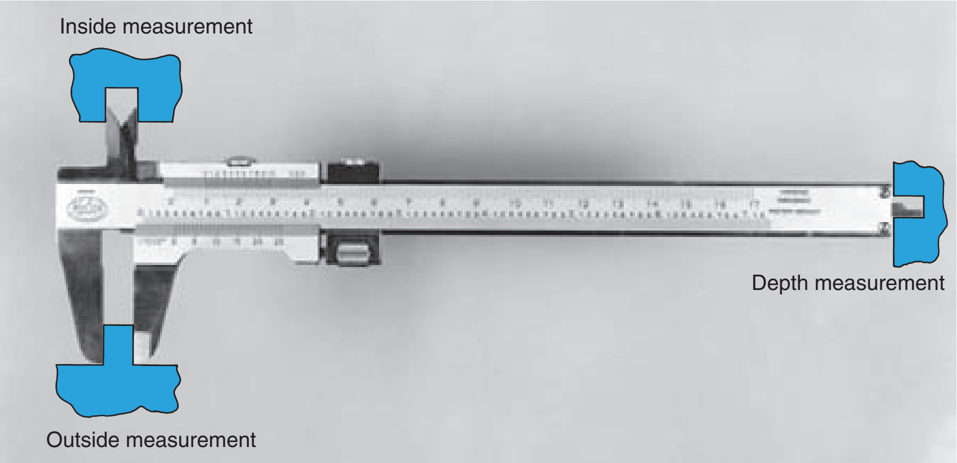


Figure C-79 Common vernier caliper.

vernier scale is to subdivide the minor divisions on the beam scale into the smallest increments that the vernier instrument is capable of measuring. For example, a 25-division vernier subdivides the minor divisions of the beam scale into 25 parts. Since the minor divisions are equal to .025 in., the vernier divides them into increments of .001 in. This is the finest discrimination of the instrument.

Most longer vernier calipers have a fine-adjustment clamp for precise adjustments of the movable jaw. Inside measurements are made over the nibs on the jaw and are read on the top scale of the vernier caliper (Figure C-78). The top scale is a duplicate of the lower scale, with the exception that it is offset to compensate for the size of the nibs.

The standard vernier caliper is a common and versatile tool because of its capacity to make outside, inside, and depth measurements (Figure C-79). Many different measuring applications are made with this particular design of vernier caliper (Figure C-80).

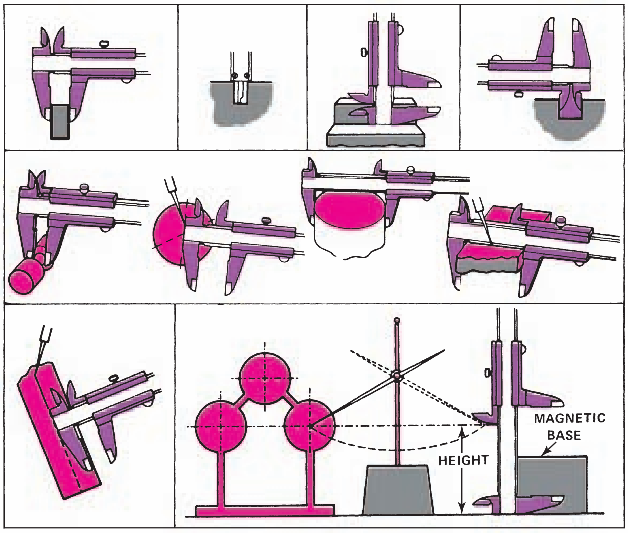


Figure C-80 The design of the vernier caliper has many applications (*Mitutoyo America Corp.*).

SHOP TIP

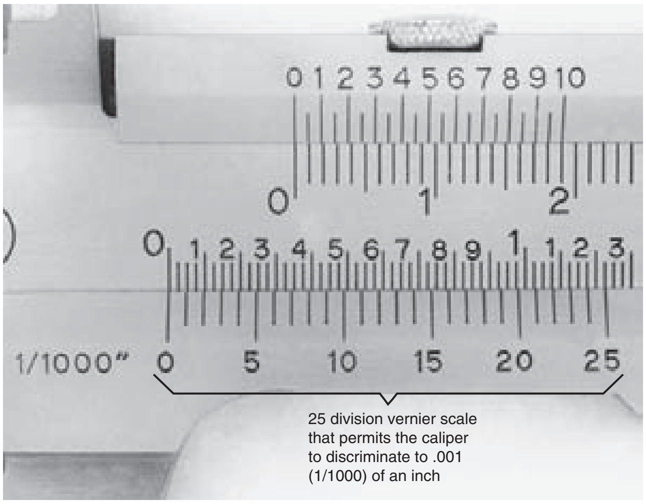
A vernier caliper is a delicate precision tool and should be treated as such. It is very important that the correct amount of pressure or feel be developed while taking a measurement. The measuring jaws should contact the workpiece firmly. However, excessive pressure will spring the jaws and give inaccurate readings. When measuring an object, use the solid jaw as the reference point, then move the sliding jaw until contact is made. When measuring with the vernier caliper, make certain that the beam of the caliper is in line with the surfaces being measured. Whenever possible, read the vernier caliper while it is still in contact with the workpiece. Moving the instrument may change the reading. Any measurement should be taken at least twice to assure reliability.

VERNIER CALIPER PROCEDURES

To test a vernier caliper for accuracy, clean the contact surfaces of the two jaws. Bring the movable jaw with normal gaging pressure into contact with the solid jaw. Hold the caliper against a light source and examine the alignment of the solid and movable jaws. If wear exists, a line of light will be visible between the jaw faces. A gap as small as $\frac{1}{10,000}$ in. can be seen against a light. If the contact between the jaws is satisfactory, check the vernier scale alignment. The vernier scale zero mark should be in alignment with the zero on the main scale. The vernier scale can be realigned to adjust it to zero on some vernier calipers.

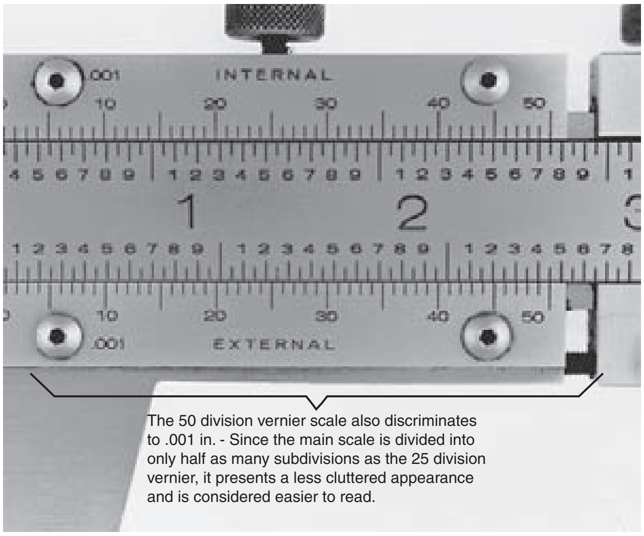
READING INCH VERNIER CALIPERS

Vernier scales are engraved with 25 or 50 divisions (Figures C-81 and C-82). On a 25-division vernier caliper, each inch on the main scale is divided into 10 major divisions numbered from 1 to 9. Each major division is .100 (100 thousandths). Each major division has four subdivisions with a spacing of .025 (twenty-five thousandths) of an inch. The vernier scale has 25 divisions, with the zero line being the index.



25 division vernier scale that permits the caliper to discriminate to .001 (1/1000) of an inch

Figure C-81 Lower scale is a 25-division vernier.



The 50 division vernier scale also discriminates to .001 in. - Since the main scale is divided into only half as many subdivisions as the 25 division vernier, it presents a less cluttered appearance and is considered easier to read.

Figure C-82 Fifty-division vernier caliper.

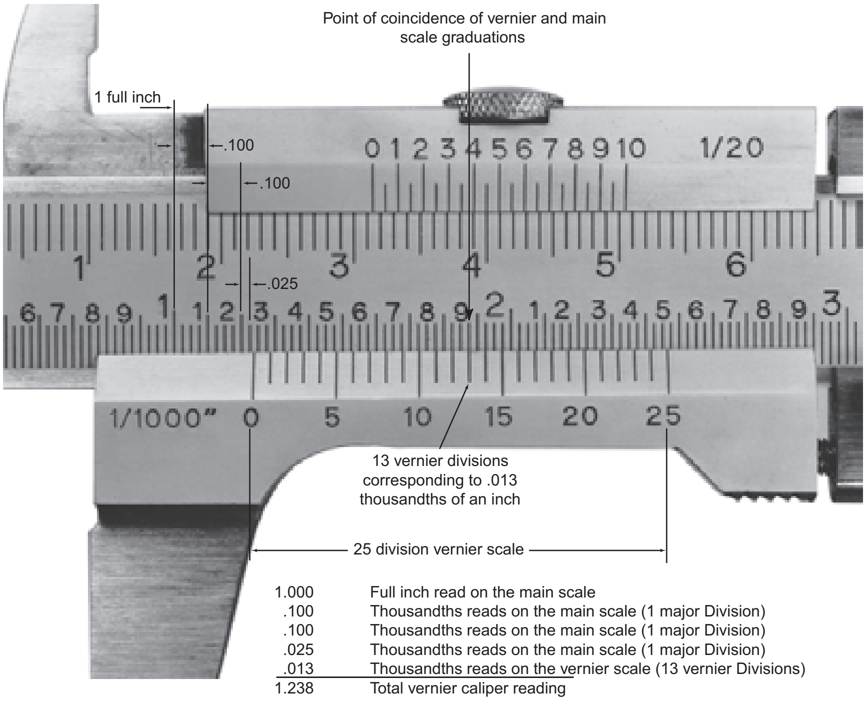
To read the vernier caliper, count all the graduations to the left of the index line. In Figure C-83 this would be 1 whole inch plus $\frac{2}{10}$ or .200, plus 1 subdivision valued at .025, plus part of one subdivision. The value of this partial subdivision is determined by the coincidence of one line on the vernier scale with one line of the true scale. For this example, the coincidence is on line 13 of the vernier scale. This is the value in thousandths of an inch that has to be added to the value read on the beam. Therefore, 1 + .100 + .100 + .025 + .013 equals the total reading of 1.238. An aid in determining the coincidental line is that the **lines adjacent to the coincidental line fall inside the lines on the true scale** (Figure C-84).

The 50-division vernier caliper shown in Figure C-85 is read as follows. Each inch on the true scale is divided into 10 major divisions of .100 in. each, with each major division subdivided in half, thus being .050 in. The vernier scale has 50 divisions. The 50-division vernier caliper reading shown is read as follows:

Beam whole-inch reading	1.000
Additional major divisions	.400
Additional minor divisions	.050
Vernier scale reading	.009
Total caliper reading	1.459

READING METRIC VERNIER CALIPERS

The applications for a metric vernier caliper are exactly the same as those described for an inch system vernier caliper.



1.000	Full inch read on the main scale
.100	Thousandths reads on the main scale (1 major Division)
.100	Thousandths reads on the main scale (1 major Division)
.025	Thousandths reads on the main scale (1 major Division)
.013	Thousandths reads on the vernier scale (13 vernier Divisions)
1.238	Total vernier caliper reading

Figure C-83 Reading a 25-division vernier caliper.

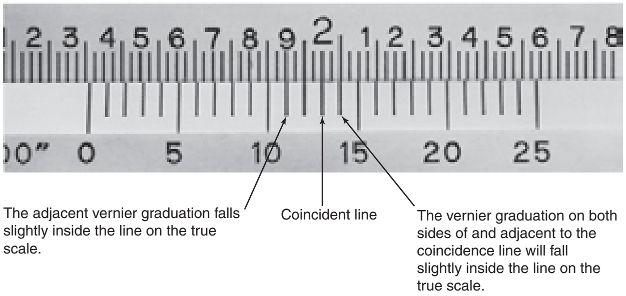
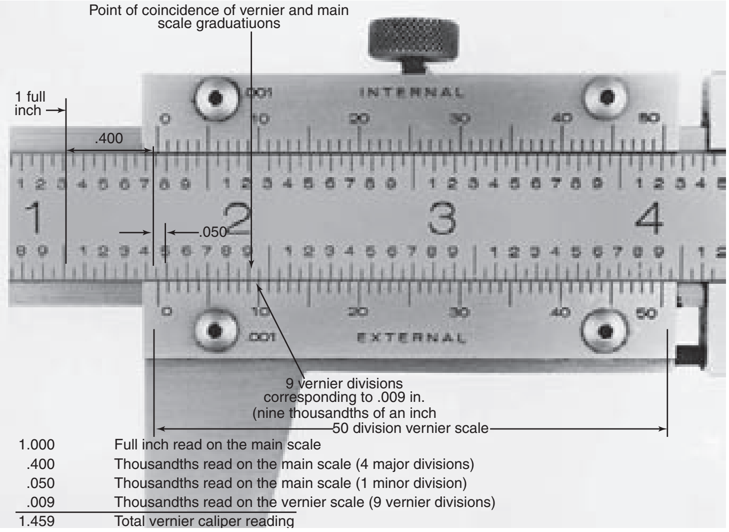


Figure C-84 Determining the coincident line on a vernier.

The discrimination of metric vernier caliper models varies among the values .02 mm, .05 mm, or .1 mm. The most commonly used type discriminates to .02 mm. The main scale on a metric vernier caliper is divided into millimeters, with every tenth millimeter mark numbered. The 10-mm line is numbered 1, the 20-mm line is numbered 2, and so on, up to the capacity of the tool (Figure C-86). The vernier scale on the sliding jaw is divided into 50 equal spaces with every fifth space numbered. Each numbered division on the vernier represents one-tenth (0.10) of a millimeter. The five smaller divisions between the numbered lines represent two-hundredths (.02) of a millimeter each.

To determine the caliper reading, read, on the main scale, whole millimeters to the left of the zero or the index line of the sliding jaw. Figure C-86 shows 27 mm plus part of an additional millimeter. The vernier scale coincides with



1.000	Full inch read on the main scale
.400	Thousandths read on the main scale (4 major divisions)
.050	Thousandths read on the main scale (1 minor division)
.009	Thousandths read on the vernier scale (9 vernier divisions)
1.459	Total vernier caliper reading

Figure C-85 Reading a 50-division vernier.

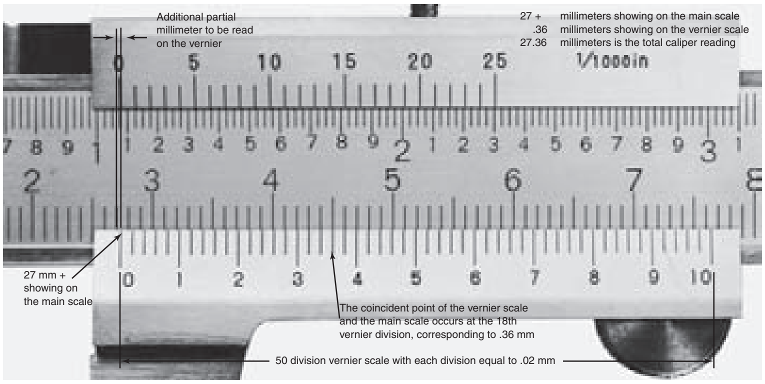


Figure C-86 Reading a metric vernier caliper with .02-mm discrimination.

the main scale at the eighteenth vernier division. Since each vernier scale spacing is equal to .02 mm, the reading on the vernier scale is equal to 18 times .02, or .36 mm. Therefore, .36 mm must be added to the amount showing on the main scale to obtain the final reading. The result is equal to 27 mm + .36 mm, or 27.36 mm.

READING VERNIER DEPTH GAGES

These measuring tools are designed to measure the depth of holes, recesses, steps, and slots. Basic parts of a vernier depth gage include the base or anvil with the vernier scale and the fine-adjustment screw (Figure C-87). Also shown is the graduated beam or bar that contains the true scale. To make accurate measurements, the reference surface must be flat and free from nicks and burrs. The base should be held firmly against the reference surface while the beam is brought in contact with the surface being measured. The measuring pressure should approximately equal the pressure exerted when making a light dot on a piece of paper with a pencil. On a vernier depth gage, dimensions are read in the same manner as on a vernier caliper.

SELF-TEST: READING INCH VERNIER CALIPERS

Determine the dimensions in the vernier caliper illustrations in Figures C-88*a* and C-88*b*.

SELF-TEST: READING METRIC VERNIER CALIPERS

Determine the metric vernier caliper dimensions illustrated in Figures C-89*a* and C-89*b*.

SELF-TEST: READING VERNIER DEPTH GAGES

Determine the depth measurements illustrated in Figures C-90*a* and C-90*b*.

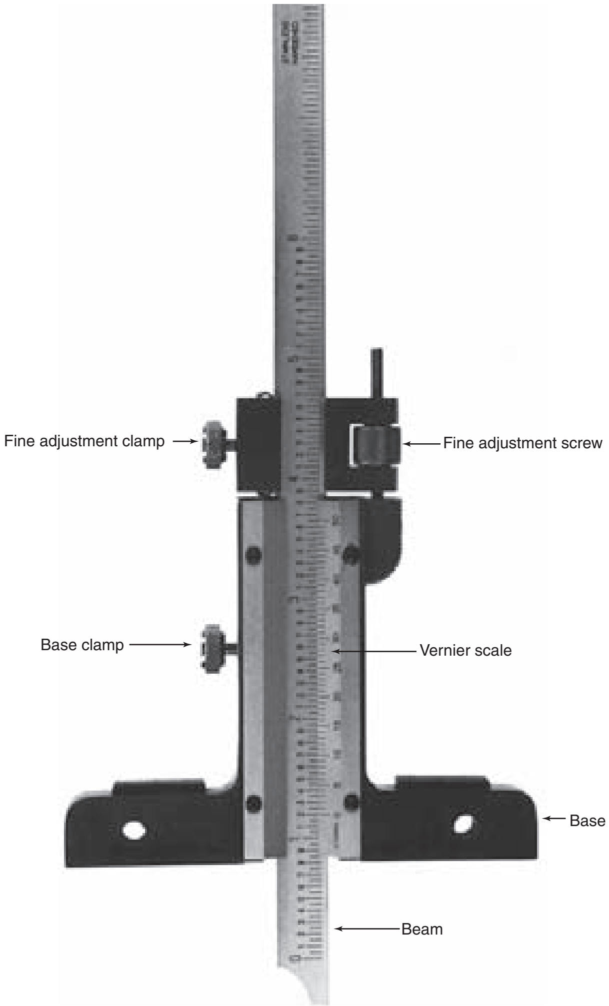


Figure C-87 Vernier depth gage with .001-in. discrimination.

MECHANICAL DIAL INSTRUMENTS FOR DIRECT MEASUREMENT

In recent years, many types of mechanical dial measuring instruments have come into wide use. These instruments are direct reading and require no interpretation of a vernier. They are extremely reliable and easy to read. Mechanical-dial

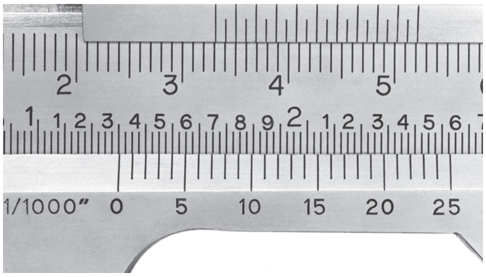


Figure C-88*a*

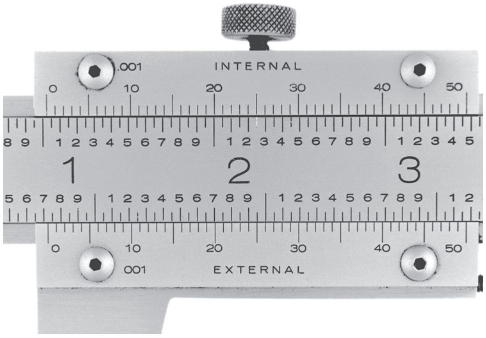


Figure C-88*b*

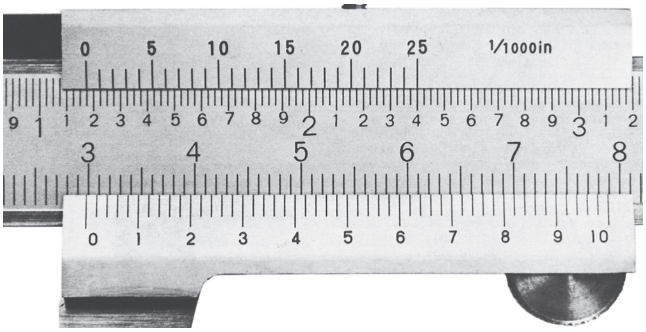


Figure C-89*a*

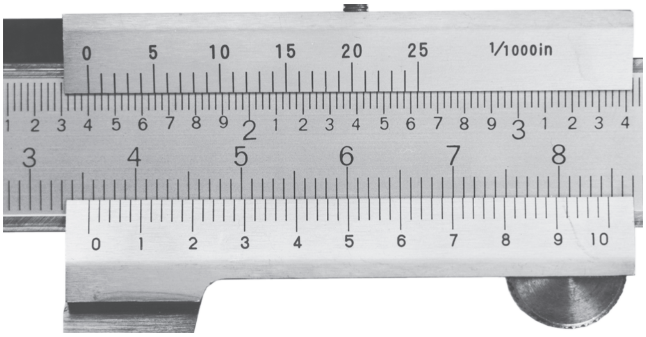


Figure C-89*b*

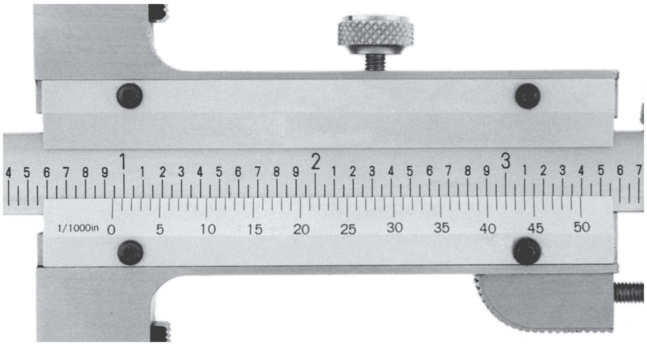


Figure C-90*a*

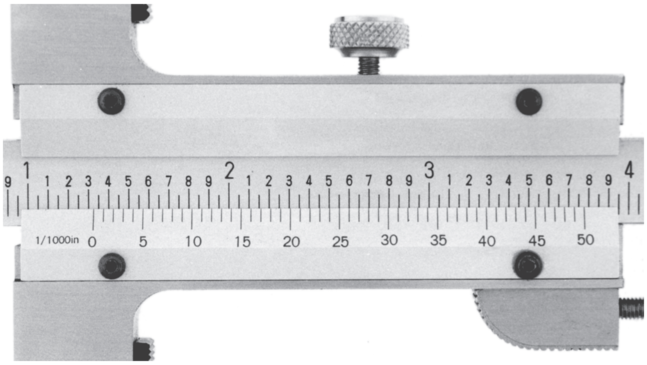


Figure C-90*b*

instruments and their electronic digital counterparts have become the industry standard and have replaced vernier instruments in many measurement applications. Common examples of these instruments include the dial caliper and the dial depth gage.

Dial Caliper

An outgrowth from the vernier caliper is the **dial caliper** (Figure C-91). However, this instrument does not employ the principle of the vernier. The beam scale on the dial caliper is graduated into only .10-in. increments. The caliper dial is graduated into either 100 or 200 divisions. The dial hand is operated by a pinion gear that engages a rack on the caliper beam. On the 100-division dial, the hand makes one complete revolution for each .10-in. movement of the sliding jaw along the beam. Therefore, each dial graduation represents $\frac{1}{100}$ of .10 in., or .001 in. maximum discrimination. On the 200-division dial the hand makes only half a revolution for each .10 in. of movement along the beam. Discrimination is also .001 in.

Since the dial caliper is direct reading, the need to determine the coincident line of a vernier scale is eliminated. This greatly facilitates reading of the instruments, and for this reason, the dial caliper has all but replaced its vernier counterpart in many applications. When using the dial caliper, remember what you have learned about the expectation of accuracy in caliper instruments.

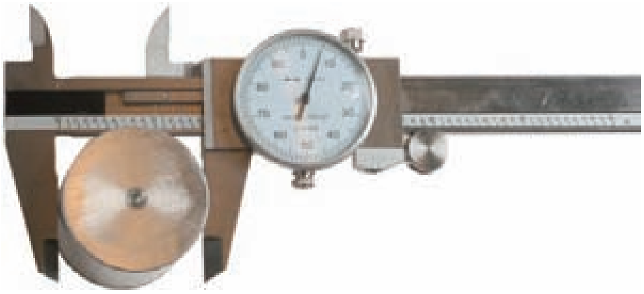


Figure C-91 Dial caliper.

Dial Depth Gages

As with vernier calipers, vernier depth gages have their dial counterparts. The dial depth gage (Figure C-92) functions in the same manner as the dial caliper. Readings are direct without the need to use a vernier scale. The dial depth gage has the capacity to measure over several inches of range, depending on the length of the beam. Discrimination is .001 in.

Another type of dial depth gage uses a dial indicator (Figure C-93). However, the capacity and discrimination of this instrument depend on the range and discrimination of the dial indicator used. The tool is used primarily in comparison measuring applications.

Digital Electronic Calipers

Integrated circuit microelectronics has revolutionized the latest generation of precision measuring instruments. An example is the electronic digital readout caliper (Figure C-94). When this instrument is coupled to a computer, printouts may be obtained, and a graph (histogram) showing how the measurements are distributed may be generated. This makes the instruments versatile for inspection purposes. As the sliding jaw moves along the beam, the position is shown on the digital display. The display may be set to zero at any point and may also be switched for inch and metric measurement.

SHOP TIP

Dial instruments tend to get dirt and chips in the gear rack. The teeth of the gear rack and the dial pinion gear are very small and closely spaced. You may not notice this problem immediately, which can cause the dial to lose its place as it moves from the zero (closed) position. As the sliding jaw is moved along, dirt or chips in the gear rack teeth may cause the dial pinion gear to skip. This will result in gross errors in the dial measurement reading. Keep the instrument as clean as possible and check occasionally to see if the sliding jaw moves freely or seems to feel gritty as it moves. If you suspect that this is a problem, close the jaws (on calipers) fully and see if the dial reads zero. Chips or a small amount of dirt on the surfaces of the caliper jaw can also cause them not to zero out correctly. Check the instrument frequently and adjust the dial position to zero if necessary or clean any dirt and chips carefully from the gear rack. A dial caliper may also be checked with a micrometer standard to see if it reads accurately at partial or full range.

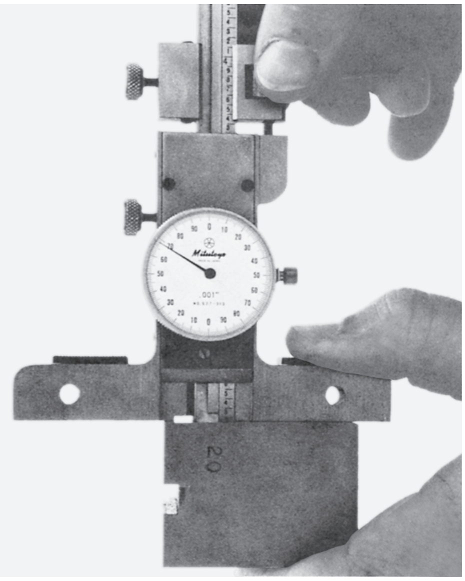


Figure C-92 Dial depth gage.

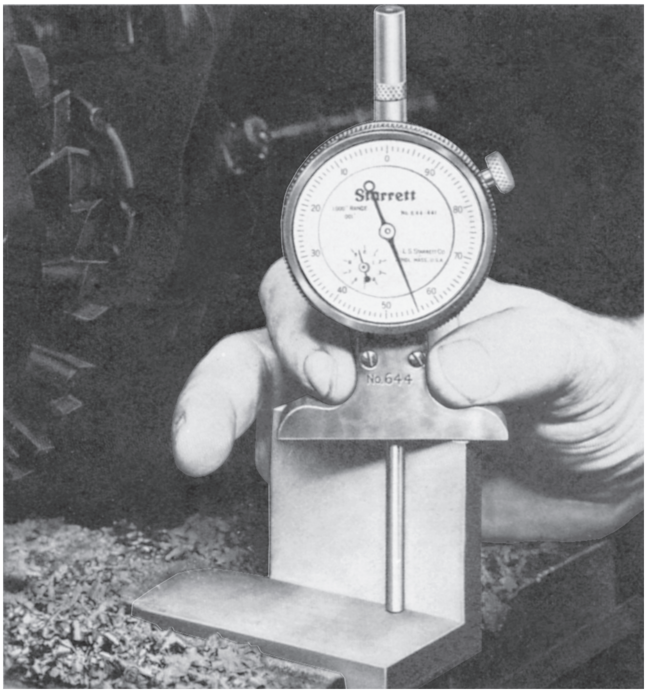


Figure C-93 Dial indicator depth gage (*Courtesy of The L.S. Starrett Co.*).

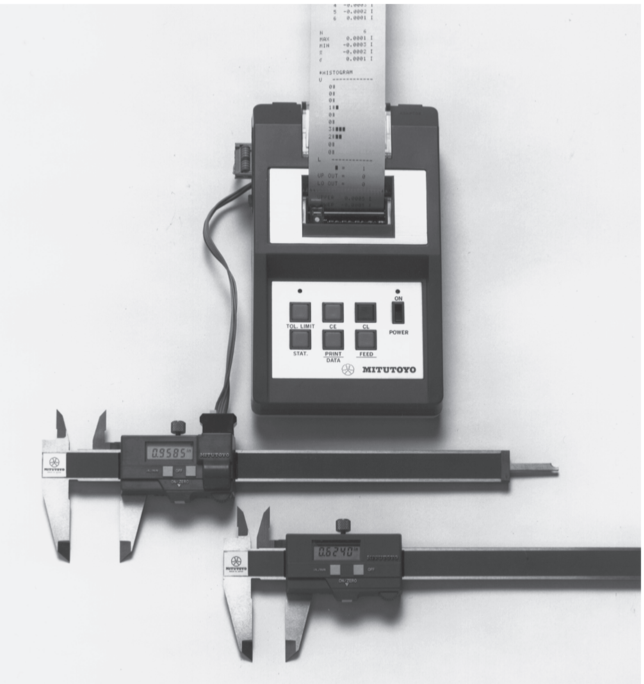


Figure C-94 Electronic calipers with computer and printer for listing and graphing measurements (*Mitutoyo America Corp.*).

INTERNET REFERENCES

Information on electronic measuring tools:

http://www.fvfowler.com
http://www.tpub.com/engine2
http://www.alibaba.com
http://mitutuyo.com
http://www.starrett.com

UNIT FOUR

Using Micrometer Instruments

Micrometer measuring instruments are the most commonly used precision measuring tools found in industry. Correct use of them is essential to anyone engaged in making or inspecting machined parts.

OBJECTIVES

After completing this unit, with the use of appropriate measuring kits, you should be able to:

- Measure and record dimensions using outside micrometers to an accuracy of ±.001 in.
- Measure and record diameters to an accuracy of ±.001 in. using an inside micrometer.
- Measure and record depth measurements using a depth micrometer to an accuracy of ±.001 in.
- Measure and record dimensions using a metric micrometer to an accuracy of ±.01 mm.
- Measure and record dimensions using a vernier micrometer to an accuracy of ±.0001 in. (assuming proper measuring conditions).

TYPES OF MICROMETER INSTRUMENTS

The common types of micrometer instruments, **outside**, **inside**, and **depth**, are discussed in detail within this unit. The micrometer appears in many other forms in addition to these common types.

Blade Micrometer

The blade micrometer (Figure C-95), so called because of its thin spindle and anvil, is used to measure narrow slots and grooves (Figure C-96) where the standard micrometer spindle and anvil cannot be accommodated because of their diameter.

Combination Metric/Inch or Inch/Metric Micrometer

The combination micrometer (Figure C-97) is designed for dual system use in metric and inch measurement. The tool has a digital reading scale for one system, and the sleeve and thimble are used for the other system.

Point Micrometer and Comparator Micrometer

The point micrometer (Figure C-98) is used in applications where limited space is available or where it might be desired to take a measurement at an exact location. Several point angles are available. The 60-degree comparator micrometer (Figure C-99) is usually called a *screw thread comparator* micrometer. It is most often used to compare screw threads with some known standard such as a thread plug gage (Figure C-100).

Disk Micrometer

The disk micrometer (Figure C-101) finds application in measuring thin materials such as paper, where a measuring face with a large area is needed. It is also useful for such measurements as the one shown in the figure where the distance from the slot to the edge is to be determined.

Figure C-95 Blade micrometer (*Courtesy of The L.S. Starrett Co.*).

Figure C-96 Blade micrometer measuring a groove.

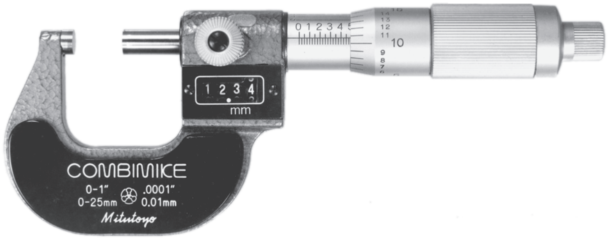


Figure C-97 Combination inch/metric micrometer.

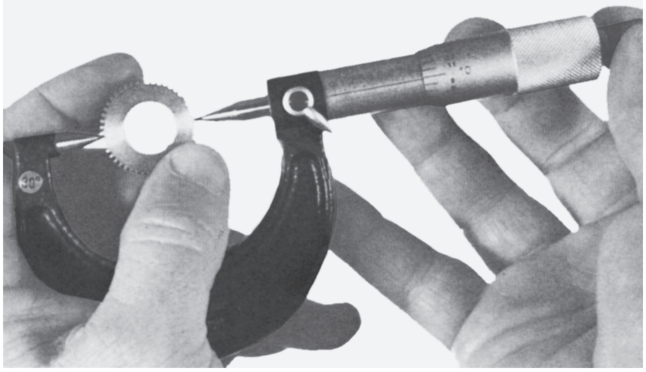


Figure C-98 Thirty-degree point comparator micrometer.

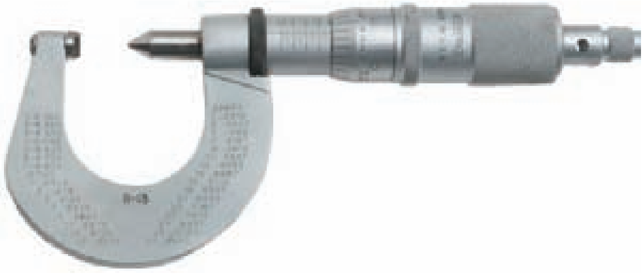


Figure C-99 Screw thread comparison micrometer.

Figure C-100 Screw thread comparison micrometer measuring a screw thread.

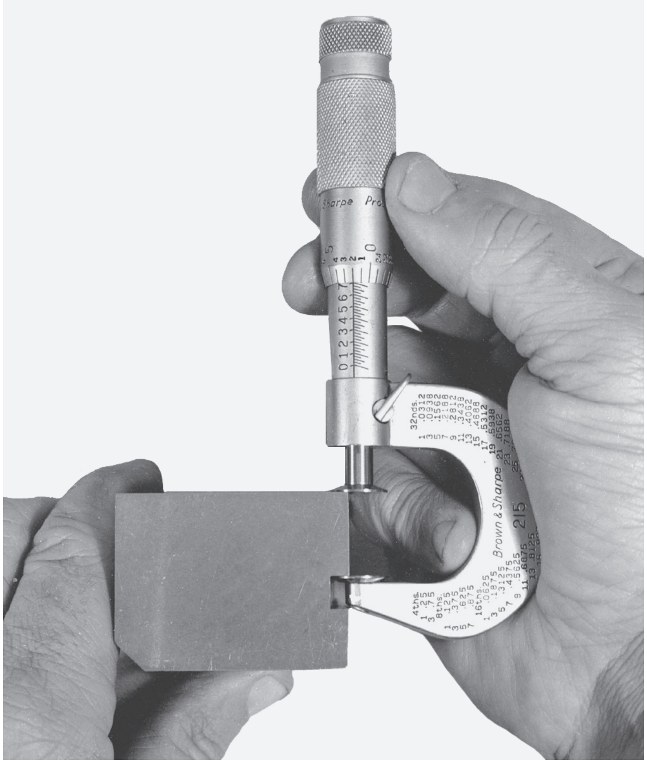


Figure C-101 Disk micrometer measuring slot-to-edge distance.

Direct-Reading Micrometer

The direct-reading micrometer, also known as a high-precision micrometer, reads directly to $\frac{1}{10,000}$ in. (Figure C-102).

Hub Micrometer

The frame of the hub micrometer (Figure C-103) is designed so that the instrument may be put through a hole or bore to measure the hub thickness of a gear or sprocket (Figure C-104).

Indicating Micrometer

The indicating micrometer (Figure C-105) is useful in inspection applications where a determination of acceptable tolerance is to be made. The instrument has an indicating mechanism built into the frame that permits a dial reading discriminating to .0005 in. When an object is measured, the size deviation above or below the micrometer setting will be indicated on the dial. This indicating micrometer has a range of ±.002 in.

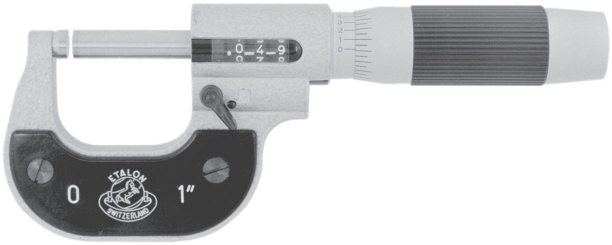


Figure C-102 Direct-reading digit micrometer.

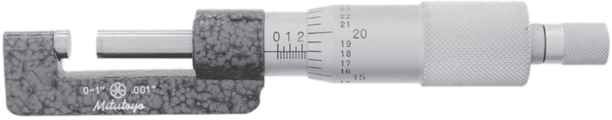


Figure C-103 Hub micrometer.

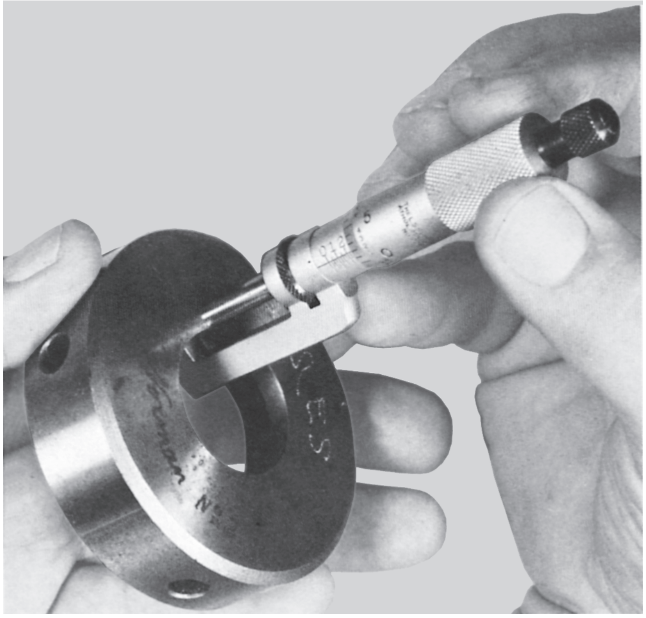


Figure C-104 Hub micrometer measuring through a bore.

Figure C-105 Indicating micrometer (*Mitutoyo America Corp.*).

Inside Micrometer Caliper

The inside micrometer caliper (Figure C-106) has jaws that resemble those on a vernier caliper. This instrument is designed for inside measurement. Thus, the versatility of the caliper and the reliability of the micrometer are combined.

Internal Micrometer

The internal micrometer (Figure C-107) uses a three-point measuring contact system to determine the size of a bore or hole. The instrument is direct reading and is more likely to yield a reliable reading because its three-point measuring contacts make the instrument self-centering as compared with a tool that uses only two contacts.

Interchangeable Anvil-Type Micrometer

The interchangeable anvil-type micrometer is often called a *multianvil* micrometer. It can be used in a variety of applications. A straight anvil is used to measure into a slot

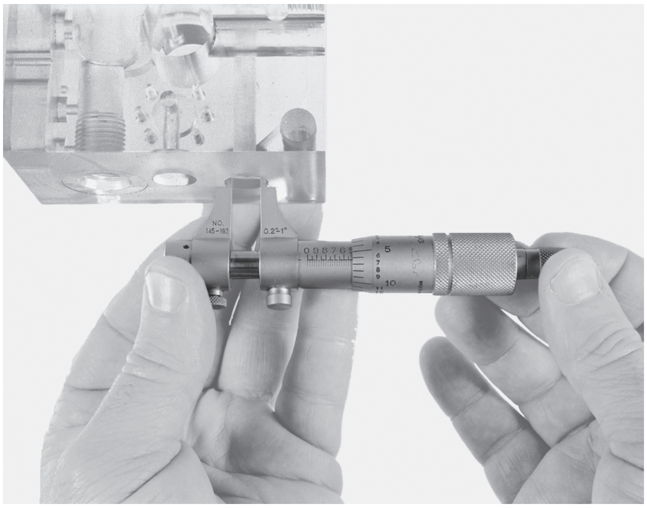


Figure C-106 Inside micrometer caliper.

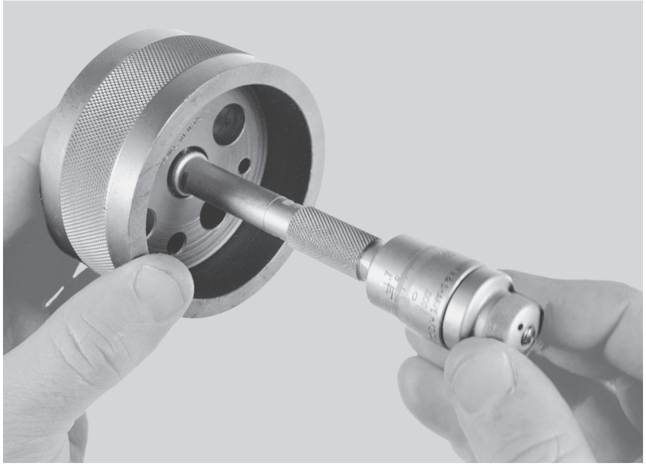


Figure C-107 Internal micrometer.

(Figure C-108). A cylindrical anvil may be used for measuring into a hole (Figure C-109). Variously shaped anvils may be clamped into position to meet special measuring requirements.

Spline Micrometer

The spline micrometer (Figure C-110) has a small-diameter spindle and anvil. The length of the anvil is considerably longer than that of the standard micrometer, and the frame of the instrument is also larger. This type of micrometer is well suited to measuring the minor diameter of a spline.

Figure C-108 Interchangeable anvil micrometer with flat anvil.

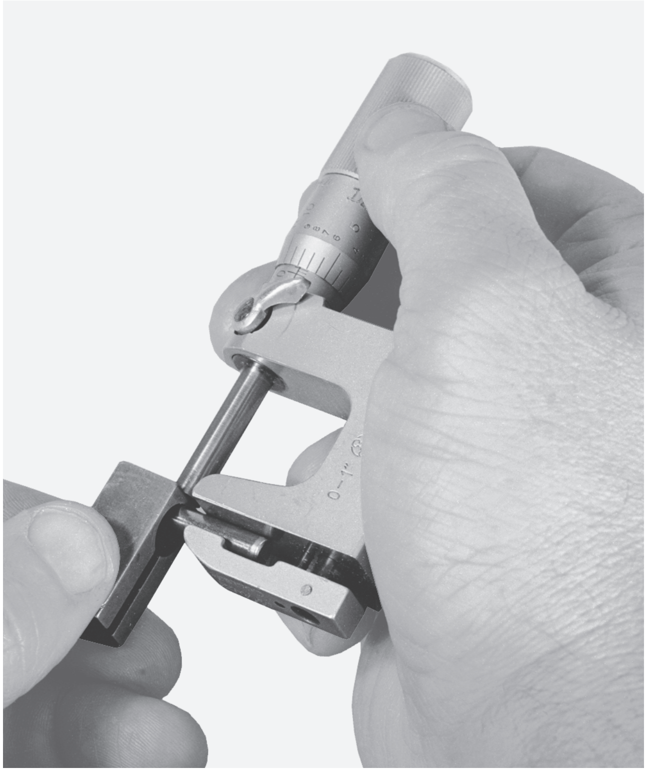


Figure C-109 Interchangeable anvil micrometer with pin anvil.

Screw Thread Micrometer

The screw thread micrometer (Figure C-111) is specifically designed to measure the pitch diameter of a screw thread. The anvil and spindle tips are shaped to match the form of the thread to be measured.

Figure C-110 Spline micrometer.

Figure C-111 Screw thread micrometer.

V-Anvil Micrometer

The V-anvil micrometer (Figure C-112) is used to measure the diameter of an object with odd-numbered symmetrical or evenly spaced features. V-angle micrometers are designed for specific numbers of these features. The type shown is for three-sided objects such as the three-fluted end mill being measured (Figure C-113). This design is also useful in checking out-of-round conditions in centerless grinding that cannot be determined with a conventional outside micrometer caliper. The next most common type of V-anvil micrometer is for five-fluted tools.

Tubing Micrometer

One type of tubing micrometer has a vertical anvil with a cylindrical-shaped tip. Another design is like the ordinary micrometer caliper except that the anvil is a half sphere instead of a flat surface. This instrument is designed to measure the wall thickness of tubing (Figure C-114). The tubing micrometer can also be applied in other applications such as determining the distance of a hole from an edge (Figure C-115).

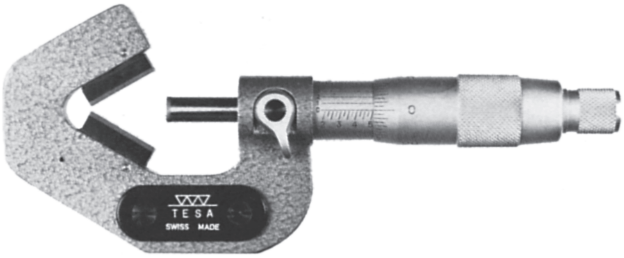


Figure C-112 V-anvil micrometer.

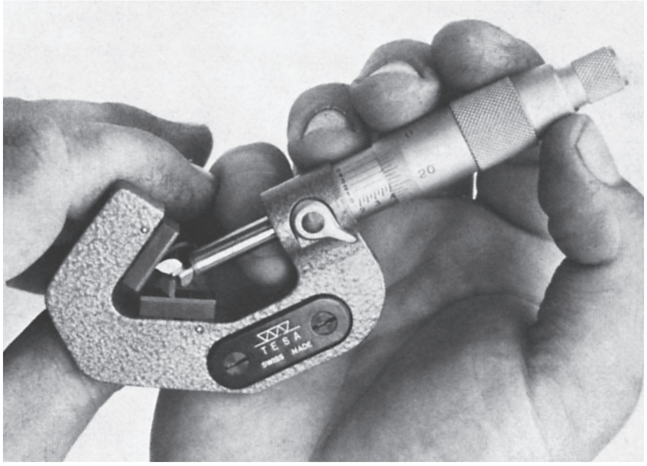


Figure C-113 V-anvil micrometer measuring a three-fluted end mill.

Figure C-114 Tubing micrometer measuring a tube wall.

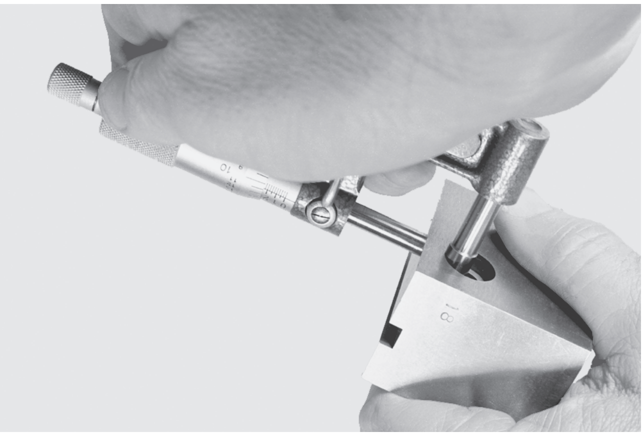


Figure C-115 Tubing micrometer measuring hole-to-edge distance.

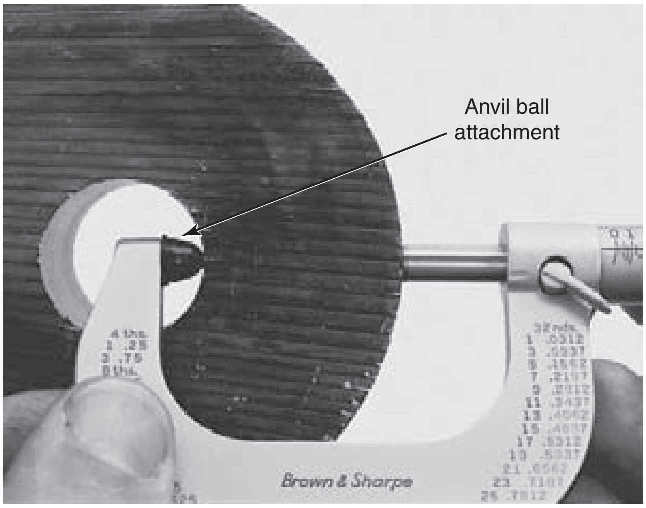


Figure C-116 Ball attachment for tubing measurement.

A standard outside micrometer may also be used to determine the wall thickness of tube or pipe (Figure C-116). In this application, a ball adapter is placed on the anvil. The diameter of the ball must be subtracted from the micrometer reading to determine the actual reading.

Caliper-Type Outside Micrometer

The caliper-type outside micrometer is used where measurements to be taken are inaccessible to a regular micrometer (Figure C-117).

Taper Micrometer

The taper micrometer can measure inside tapers (Figure C-118) or outside tapers (Figure C-119).

Groove Micrometer

The groove micrometer (Figure C-120) is well suited to measuring grooves and slots, especially in inaccessible places such as bores.

Digital Electronic Micrometers

As with calipers and many other common measuring tools, micrometers are also available in electronic digital readout models (Figure C-121). The instruments are easy to read,

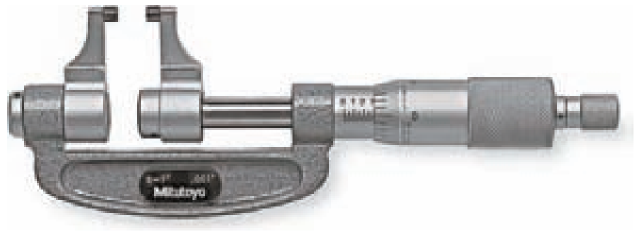


Figure C-117 Caliper-type outside micrometer (*Mitutoyo America Corp*.).

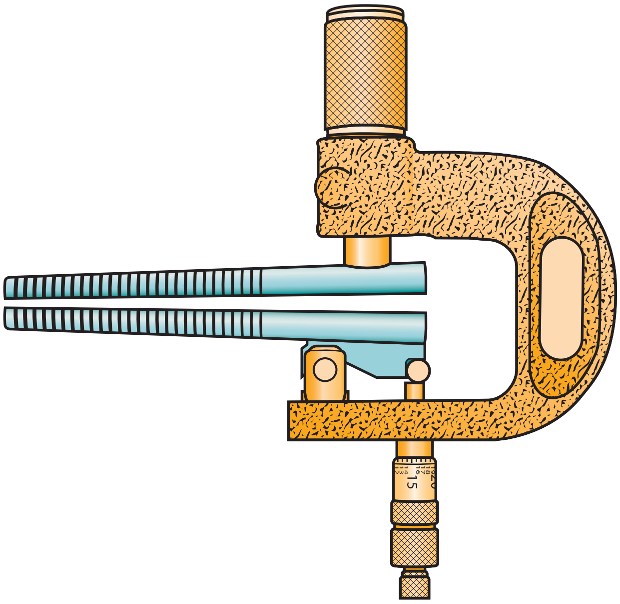


Figure C-118 Inside taper micrometer.

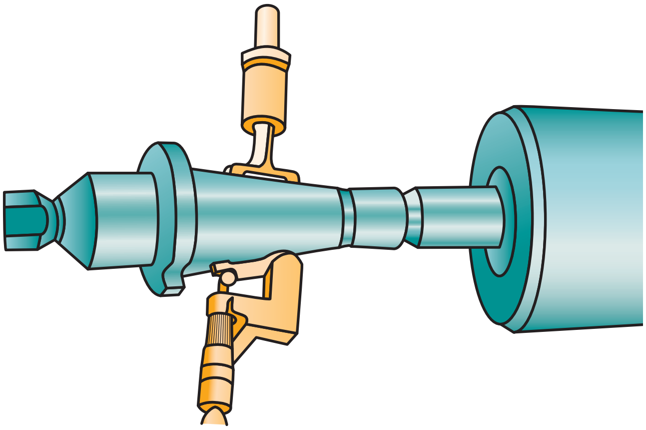


Figure C-119 Outside taper micrometer in use.

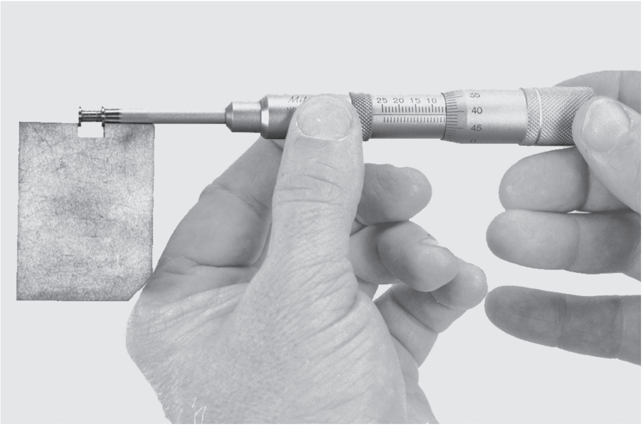


Figure C-120 Groove micrometer.

Figure C-121 Digital readout micrometers are available in a wide variety of styles (*Mitutoyo America Corp.*).

highly accurate, and available in all the common styles of their mechanical counterparts.

DISCRIMINATION OF MICROMETER INSTRUMENTS

The standard micrometer will discriminate to .001 ($\frac{1}{1000}$) in. In the vernier form, the discrimination is increased to .0001 ($\frac{1}{10{,}000}$) in. The common metric micrometer discriminates to .01 ($\frac{1}{100}$) mm. The same rules apply to micrometers as apply to all other measuring instruments. The tool should not be used beyond its discrimination. A standard micrometer with .001 discrimination should not be used in an attempt to ascertain measurements beyond that point. To measure to a discrimination of .0001 with the vernier micrometer, certain special conditions must be met. These will be discussed in more detail within this unit.

RELIABILITY AND EXPECTATION OF ACCURACY IN MICROMETER INSTRUMENTS

The micrometer is more reliable than the vernier. One reason for this is instrument readability. The .001-in. graduations that dictate the maximum discrimination of the micrometer are placed on the circumference of the thimble. The distance between the marks is therefore increased, making them easier to see.

The micrometer will yield reliable results to .001 in. discrimination if the instrument is properly cared for and properly calibrated, and if correct procedure for use is followed. Care and procedure will be discussed in detail within this unit. **Calibration** is the process by which any measuring instrument is compared with a known standard. If the tool deviates from the standard, it may then be adjusted to conformity. This is an additional advantage of the micrometer over the vernier. The micrometer must be periodically calibrated if reliable results are to be obtained.

Can a micrometer measure reliably to within .001 in.? The answer is no for the standard micrometer, as this violates the 10 to 1 rule for discrimination. The answer is yes for the vernier micrometer, but only under controlled conditions. What then, is an acceptable expectation of accuracy that will yield maximum reliability? This is dependent to some degree on the tolerance specified and can be summarized in the following table:

Tolerance Specified	Acceptability of the Standard Micrometer	Acceptability of the Vernier Micrometer
+.000–.001 *or* +.001–.000	No	Yes (under controlled conditions)
±.001	Yes	Yes (vernier will not be required)

For a specified tolerance within .001 in., the vernier micrometer should be used. Plus or minus .001 in. is a total range of .002 in., which falls within the capability of the standard micrometer.

The micrometer is indeed a marvelous example of precision manufacturing. This rugged tool is produced in quantity, with each one conforming to equally high standards. Micrometer instruments, in all their many forms, constitute one of the fundamental measuring instruments for the machinist.

CARE OF OUTSIDE MICROMETERS

You should be familiar with the names of the major parts of the typical outside micrometer (Figure C-122). The micrometer uses the movement of a precisely threaded rod turning in a nut for precision measurements. The accuracy of micrometer measurements depends on the quality of the tool's construction, the care it receives, and the skill of the user. A micrometer should be wiped clean of dust and oil before and after use. A micrometer should not be opened or closed by holding it by the thimble and spinning the frame around the axis of the spindle, and a micrometer should not be dropped. Even a fall of a short distance can spring the

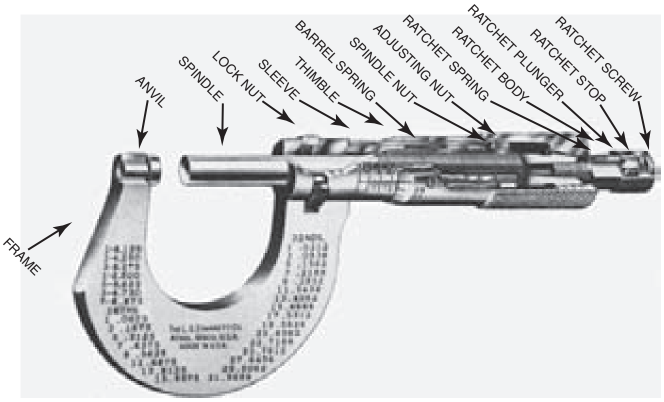


Figure C-122 Parts of the outside micrometer (*Courtesy of The L.S. Starrett Co.*).

frame. This will cause misalignment between the anvil and spindle faces and destroy the accuracy of this precision tool. A micrometer should be kept away from chips on a machine tool. The instrument should be placed on a clean tool board (Figure C-123) or on a clean shop towel (Figure C-124) close to where it is needed.

Always remember that the machinist is responsible for any measurements he or she may make. To excuse an inaccurate measurement on the grounds that a micrometer was not properly adjusted or cared for would be less than professional. When a micrometer is stored after use, the spindle face should not touch the anvil. Perspiration, moisture from the air, or even oils promote corrosion between the measuring faces, with a corresponding reduction in accuracy.

Prior to using a micrometer, clean the measuring faces. The measuring faces of many newer micrometers are made from the extremely hard metal tungsten carbide. These instruments are often known as *carbide-tipped micrometers*. If you examine the measuring faces of a carbide-tipped micrometer, you will see where the carbide has been attached to the face of the anvil and spindle. Carbide-tipped micrometers have durable and long-wearing measuring faces. Screw the spindle down lightly against a piece of paper held between it and the anvil (Figure C-125). Slide the paper out from between the measuring faces and blow away any fuzz that clings to the spindle or anvil. At this time, test the zero reading of the micrometer by bringing the spindle slowly into contact with the anvil (Figure C-126). Use the ratchet stop or friction thimble to perform this operation. The ratchet stop or friction thimble found on most micrometers is designed to equalize the gaging force. When the spindle and anvil contact the workpiece, the ratchet stop or friction thimble will slip as a predetermined amount of torque is applied to the micrometer thimble. If the micrometer does not have a ratchet device, use your thumb and index finger to provide a slip clutch effect on the thimble. Never use more pressure when checking the zero reading than when making actual measurements on the workpiece. If there is a small error, it may be corrected by adjusting the index line to the zero point (Figure C-127). Follow the manufacturer's instructions provided with the micrometer when making this adjustment. Also follow the manufacturer's instructions for correcting a loose thimble-to-spindle connection or

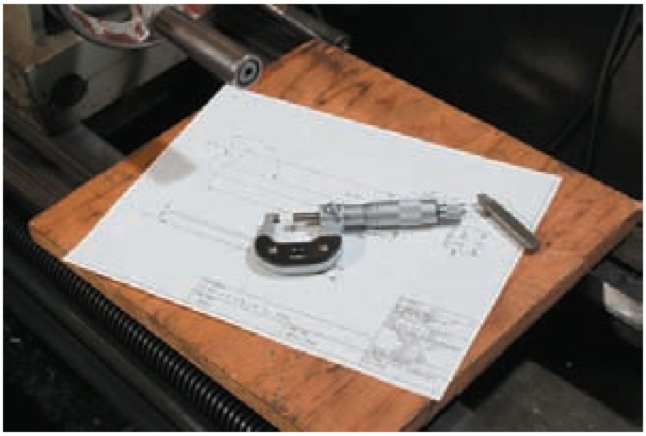


Figure C-123 Micrometers should always be kept on a tool board when used near a machine tool.

Figure C-124 Micrometers should be kept on a clean shop towel when used on the bench.

Figure C-125 Cleaning the measuring faces.

Figure C-126 Checking the zero reference.

Figure C-127 Adjusting the index line to zero.

incorrect friction thimble or ratchet stop action. One drop of instrument oil applied to the micrometer thread at monthly intervals will help it provide many years of reliable service. Machinists are often judged by their associates on the way they handle and care for their tools. Those who care for their tools properly will more likely be held in higher professional regard.

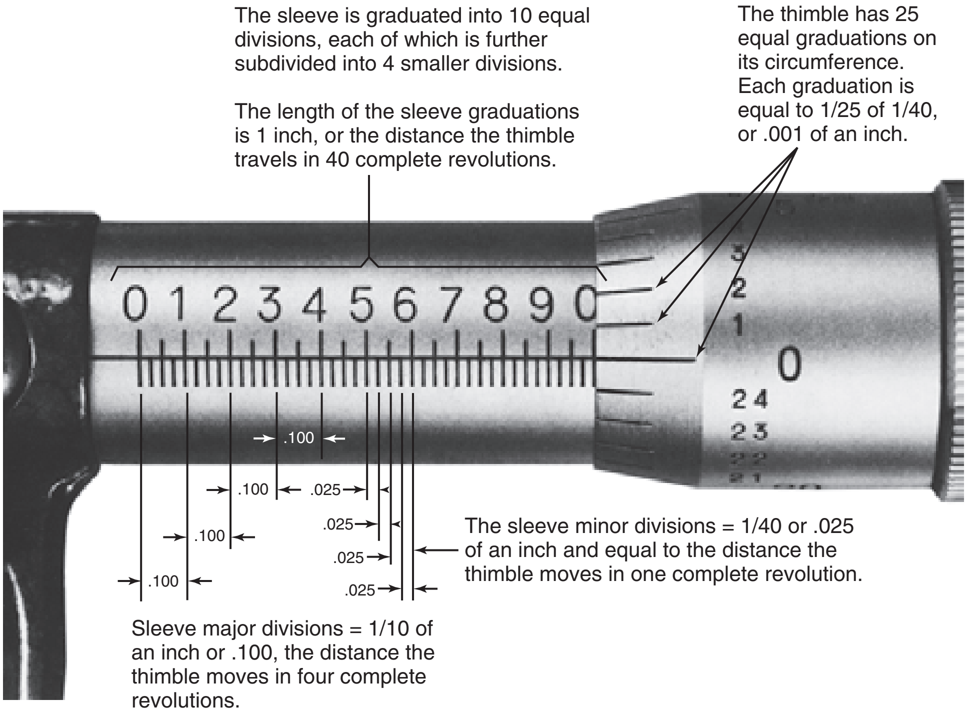
READING INCH MICROMETERS

Dimensions requiring the use of micrometers will generally be expressed in decimal form to three decimal places. In the case of an inch instrument, this is the thousandths place. You should think in terms of thousandths whenever reading decimal fractions. For example, the decimal .156 in. is read as one hundred fifty-six thousandths of an inch. Likewise, .062 in. is read as 62 thousandths of an inch.

On the **sleeve** of the micrometer is a graduated scale with 10 numbered divisions, $\frac{1}{10}$ in. or .100 in. (100 thousandths) apart. Each of these major divisions is further subdivided into four equal parts, which makes the distance between these graduations $\frac{1}{4}$ of .100 in., or .025 in. (25 thousandths) (Figure C-128). The **spindle screw** of a micrometer has 40 threads per inch. When the spindle is turned one complete revolution, it moves $\frac{1}{40}$ of an inch, or, expressed as a decimal, .025 in. (25 thousandths).

When you examine the **thimble**, you will find 25 evenly spaced divisions around its circumference (Figure C-128). Because each complete revolution of the thimble causes it to move a distance of .025 in., each thimble graduation must be equal to $\frac{1}{25}$ of .025 in., or .001 in (one thousandth). On most micrometers, each thimble graduation is numbered to facilitate reading the instrument. On older micrometers, only every fifth line may be numbered.

When reading the micrometer (Figure C-129), first determine the value indicated by the lines exposed on the sleeve. The edge of the thimble exposes three major divisions. This represents .300 in. (300 thousandths). However, there are also two minor divisions showing on the sleeve. The value of these is .025, for a total of .050 in. (50 thousandths). The reading on the thimble is 9, which indicates .009 in. (9 thousandths). The final micrometer reading is determined by adding the total of the sleeve and thimble readings. In the example shown (Figure C-129), the sleeve



The sleeve is graduated into 10 equal divisions, each of which is further subdivided into 4 smaller divisions.

The length of the sleeve graduations is 1 inch, or the distance the thimble travels in 40 complete revolutions.

The thimble has 25 equal graduations on its circumference. Each graduation is equal to 1/25 of 1/40, or .001 of an inch.

The sleeve minor divisions = 1/40 or .025 of an inch and equal to the distance the thimble moves in one complete revolution.

Sleeve major divisions = 1/10 of an inch or .100, the distance the thimble moves in four complete revolutions.

Figure C-128 Graduations on the inch micrometer.

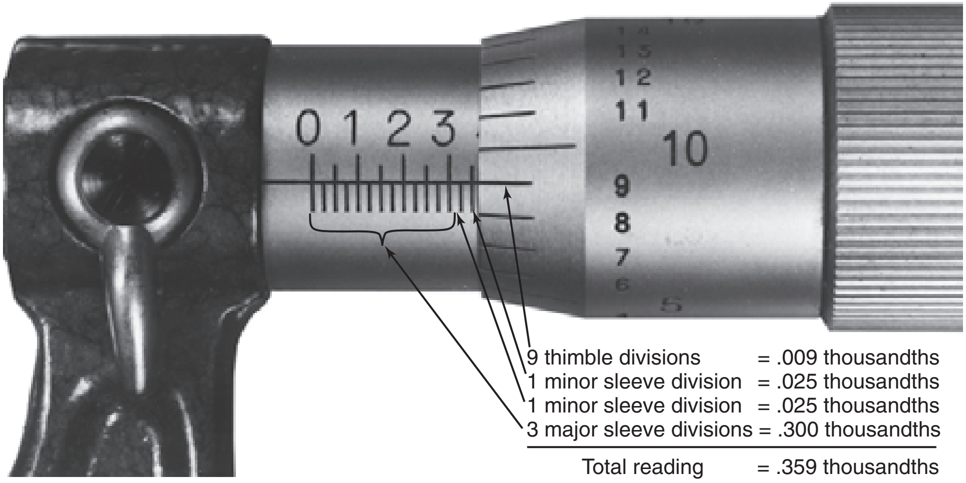


Figure C-129 Inch micrometer reading of .359, or three hundred fifty-nine thousandths.

shows a total of .350 in. Adding this value to the thimble gives the final reading: .350 in. + .009 in., or .359 in.

USING THE MICROMETER

A micrometer should be gripped by the **frame** (Figure C-130), leaving the thumb and forefinger free to operate the thimble. When possible, take micrometer readings while the instrument is in contact with the workpiece (Figure C-131). Use only enough pressure on the **spindle** and **anvil** to yield a reliable result. This is what the machinist refers to as **feel**. The proper feel of a micrometer will come only from experience. Obviously, excessive pressure will not only result in an inaccurate measurement but will also distort the frame of the micrometer and possibly damage it permanently. You should also remember that too light a pressure on the part by the measuring faces can yield an unreliable result.

The micrometer should be held in both hands whenever possible. This is especially true when measuring cylindrical workpieces (Figure C-132). Holding the instrument in one hand does not permit sufficient control for reliable readings. Furthermore, cylindrical workpieces should be checked at least twice with **measurements made 90 degrees apart**. This is to check for an out-of-round condition (Figure C-133). When critical dimensions are measured, that is, any dimension where

Figure C-130 Proper way to hold a micrometer.

Figure C-131 Read a micrometer while it is still in contact with the workpiece.

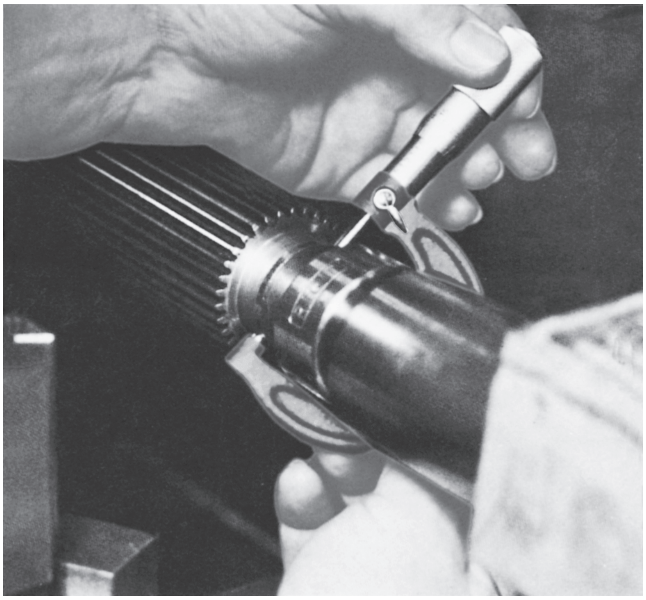


Figure C-132 Hold a micrometer in both hands when measuring a round part.

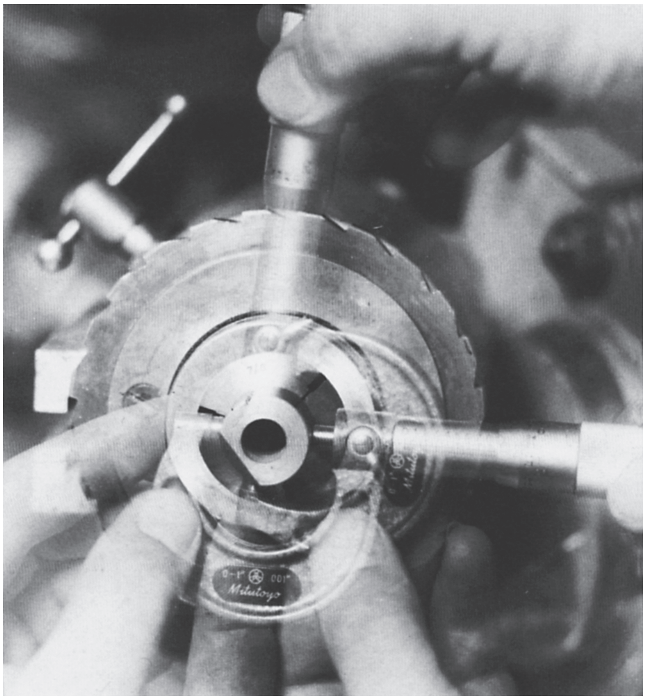


Figure C-133 When measuring round parts, take two readings 90 degrees apart.

a small amount of tolerance is acceptable, at least two consecutive measurements should be made. Both readings should indicate identical results. If two identical readings cannot be determined, then the actual size of the part cannot be stated reliably. **All critical measurements should be made at a temperature of 68° Fahrenheit (20° Celsius).** A workpiece warmer than this temperature will be larger because of heat expansion.

SHOP TIP

When using a 0- to 1-in.-range micrometer always check the zero reference before making any measurements with the tool. When using micrometers with larger ranges, use the micrometer's standard or gage blocks to verify that the tool's extreme lower and extreme upper range readings zero out correctly.

Outside micrometers usually have a measuring range of 1 in. They are identified by size according to the largest dimensions they measure. A 2-in. micrometer will measure from 1 to 2 in. A 3-in. micrometer will measure from 2 to 3 in. The capacity of the tool is increased by increasing the size of the frame. Typical outside micrometers range in capacity from 0 to 168 in. It requires a great deal more skill to get consistent measurements with large-capacity micrometers.

SELF-TEST

1. Why should a micrometer be kept clean and protected?
2. Why should a micrometer be stored with the spindle out of contact with the anvil?
3. Why are the measuring faces of the micrometer cleaned before measuring?
4. How precise is the standard micrometer?
5. What affects the accuracy of a micrometer?
6. What is the difference between the sleeve and thimble?
7. Why should a micrometer be read while it is still in contact with the object to be measured?
8. How often should an object be measured to verify its actual size?
9. What effect has an increase in temperature on the size of a part?
10. What is the purpose of the friction thimble or ratchet stop on the micrometer?
11. Read and record the five outside micrometer readings in Figures C-134*a* to C-134*e*.

Figure C-134*a*

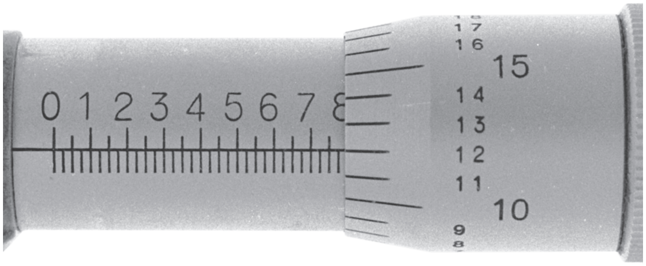


Figure C-134*b*

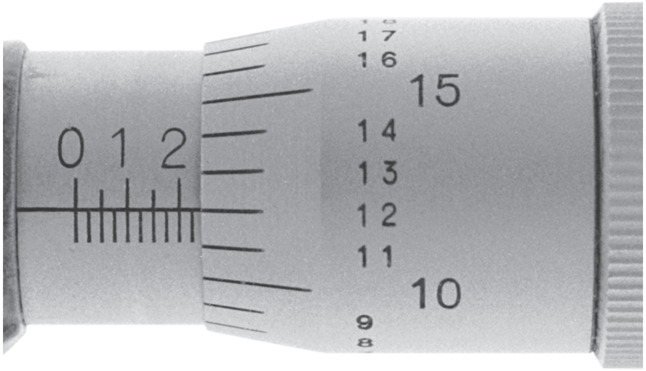


Figure C-134*c*

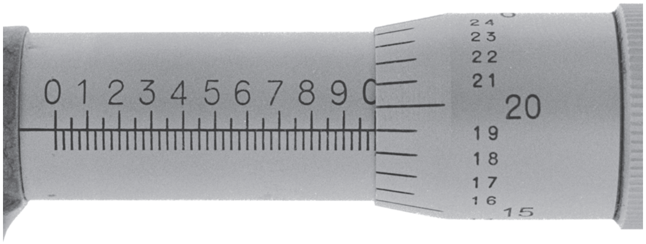


Figure C-134*d*

Figure C-134*e*

USING INSIDE MICROMETERS

Inside micrometers are equipped with the same graduations as outside micrometers. Inside micrometers discriminate to .001 in. and have a measuring capacity ranging from 1.5 to 20.0 in. or more. A typical **tubular type** inside micrometer set (Figure C-135) consists of the **micrometer head** with detachable **hardened anvils** and several **tubular measuring rods** with **hardened contact tips**. The lengths of these rods differ in increments of .5 in. to match the measuring capacity of the micrometer head, which in this case is .5 in. A handle is provided to hold the instrument in places where holding the instrument directly would be difficult. Another common type of inside micrometer comes equipped with relatively small diameter solid rods that differ in inch increments, even though the head movement is .5 in. In this case, a .5-in. spacing collar is provided. This can be slipped over the base of the rod before it is inserted into the measuring head.

Inside micrometer heads have a range of .250, .500, 1.000, or 2.000 in., depending on the total capacity of the set. For example, an inside micrometer set with a head range of .500 in. will be able to measure from 1.500 to 12.500 in.

The measuring range of the inside micrometer is changed by attaching the extension rods. Extension rods may be solid or tubular. Tubular rods are lighter in weight and are often found in large-range inside micrometer sets. Tubular rods are also more rigid. It is important that all parts be **extremely clean** when changing extension rods (Figure C-136). Even small dust particles can affect the accuracy of the instrument.

Figure C-135 Tubular inside micrometer set.

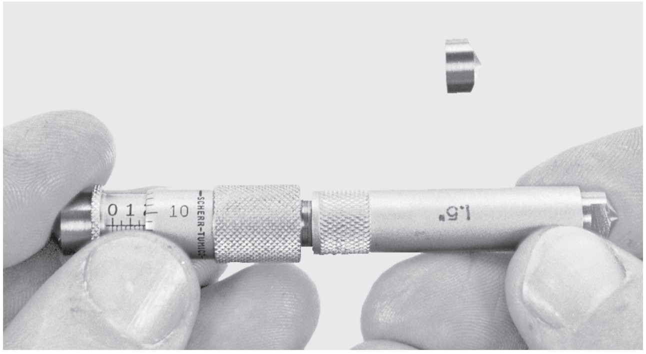


Figure C-136 Attaching a 1.5-in. extension rod to an inside micrometer head.

When making internal measurements, set one end of the inside micrometer against one side of the hole to be measured (Figure C-137). An inside micrometer should not be held in the hands for extended periods, as the resultant heat may affect the accuracy of the instrument. A handle is usually provided, which eliminates the need to hold the instrument and also facilitates insertion of the micrometer into a bore or hole (Figure C-138). One end of the micrometer will become the center of the arcing movement used when finding the centerline of the hole to be measured. The micrometer should then be adjusted to the size of the hole. When the correct hole size is reached, there should be a light drag between the measuring tip and the work when the tip is moved through the centerline of the hole. The size of the hole is determined by adding the reading of the micrometer head, the length of the extension rod, and the length of the spacing collar, if one was used. Read the micrometer **while it is still in place if possible**. If the instrument must be removed to be read, the correct range can be determined by checking with a rule (Figure C-139). A skilled worker will usually use an **accurate outside micrometer to verify** a reading taken with an inside micrometer. In this case, the inside micrometer becomes an easily adjustable transfer measuring tool (Figure C-140). Take at least two readings 90 degrees apart to obtain the size of a hole or bore. The readings should be identical. Inside micrometers do not have a spindle lock; therefore, to prevent the spindle from turning while establishing the correct feel, maintain the adjusting nut slightly tighter than normal.

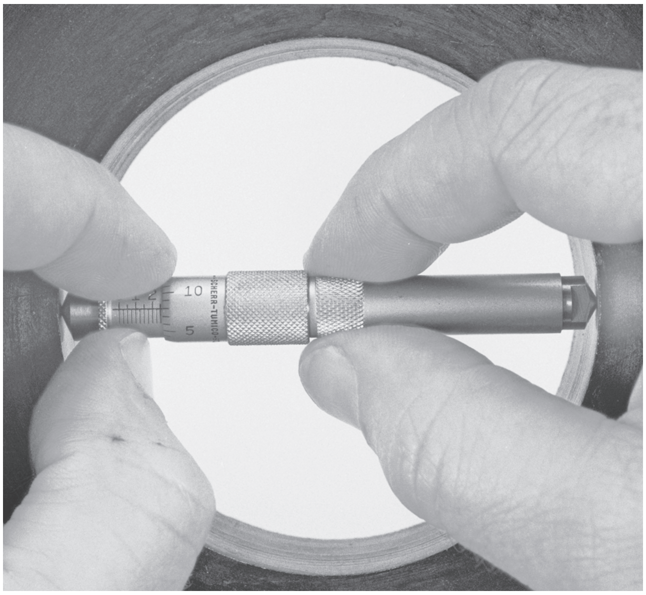


Figure C-137 Placing the inside micrometer in the bore to be measured.

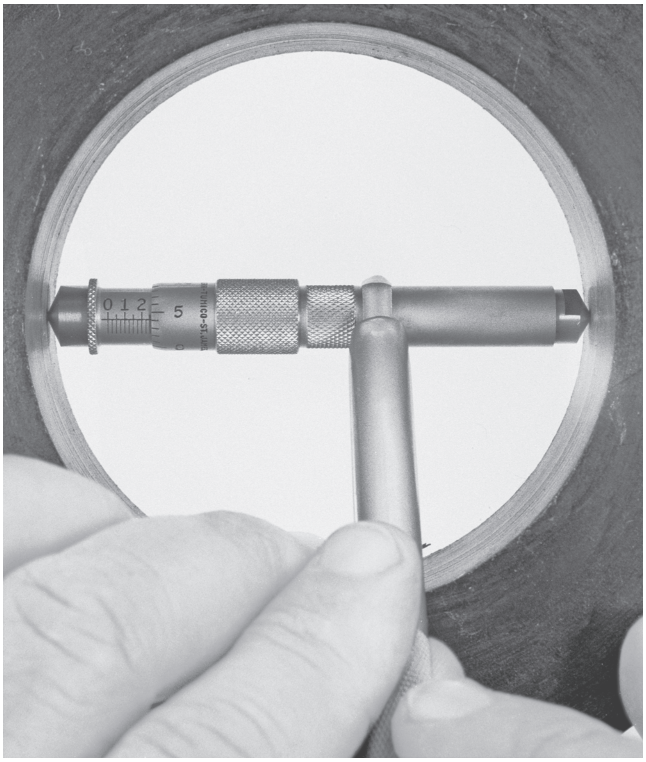


Figure C-138 Inside micrometer head used with a handle.

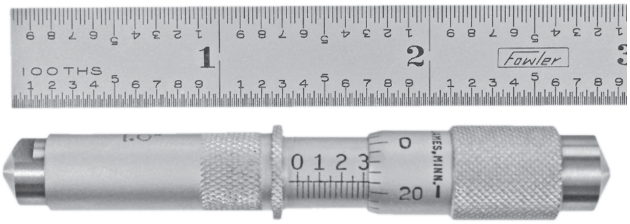


Figure C-139 Confirming inside micrometer range using a rule.

Figure C-140 Checking the inside micrometer with an outside micrometer.

SELF-TEST

Read and record the five inside micrometer readings shown in Figures C-141*a* to C-141*e*. The micrometer head is 1.500 in. when zeroed.

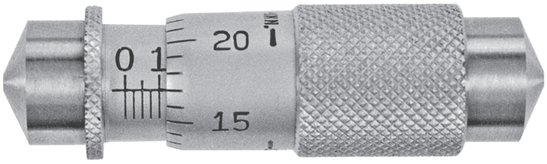


Figure C-141*a*

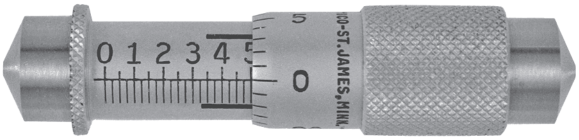


Figure C-141*b*

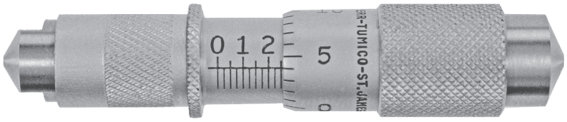


Figure C-141*c*

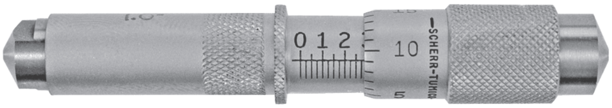


Figure C-141*d*

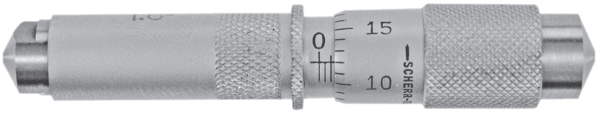


Figure C-141*e*

Obtain an inside micrometer set from your instructor and practice using the instrument on objects around your laboratory. Measure examples such as lathe spindle holes, bushings, bores of roller bearings, hydraulic cylinders, and tubing.

USING DEPTH MICROMETERS

A **depth micrometer** is a tool used to measure precisely depths of holes, grooves, shoulders, and recesses. Like other micrometer instruments, it will discriminate to .001 in. Depth micrometers usually come as a set with interchangeable rods to accommodate different depth measurements (Figure C-142). The basic parts of the depth micrometer are the **base**, **sleeve**, **thimble**, **extension rod**, **thimble cap**, and, frequently, a **rachet stop**. The base of depth micrometers can be of various widths. Generally the wider bases are more stable, but in many instances, space limitations dictate the use of narrower bases. Some depth micrometers are made with only a half base for measurements in confined spaces.

Figure C-142 Depth micrometer set.

The extension rods are installed or removed by holding the thimble and unscrewing the thimble cap. Make sure that the seat between the thimble cap and rod adjusting nuts is clean before reassembling the micrometer. Do not overtighten when replacing the thimble cap. Furthermore, **do not attempt to adjust the rod length by turning the adjusting nuts.** These rods are factory adjusted and matched as a set. **The measuring rods from a specific depth micrometer set should always be kept with that set**. Since these rods are factory adjusted and matched to a specific instrument, **transposing measuring rods** from set to set **will usually result in incorrect measurements**.

When making depth measurements, it is important that the micrometer base has a smooth and flat surface on which to rest. Furthermore, sufficient pressure must be applied to keep the base in contact with the reference surface. When a depth micrometer is used without a ratchet, a slip clutch effect can be produced by letting the thimble slip while turning it between the thumb and index finger (Figure C-143).

READING INCH DEPTH MICROMETERS

When a comparison is made between the sleeve of an outside micrometer and the sleeve of a depth micrometer, note that the graduations are numbered in the opposite direction (Figure C-144). When reading a depth micrometer, the distance to be measured is the value covered by the thimble. Consider the reading shown in Figure C-144. The thimble edge is between the numbers 5 and 6. This indicates a value of at least .500 in. on the sleeve major divisions. The thimble also covers the first minor division on the sleeve, which has a value of .025 in. The value on the thimble circumference indicates

Figure C-143 Proper way to hold the depth micrometer.

10 thimble divisions = .010 thousandths
1 minor sleeve division (covered by thimble) = .025 thousandths
5 major sleeve divisions (covered by thimble) = .500 thousandths
Total micrometer reading = .535 thousandths

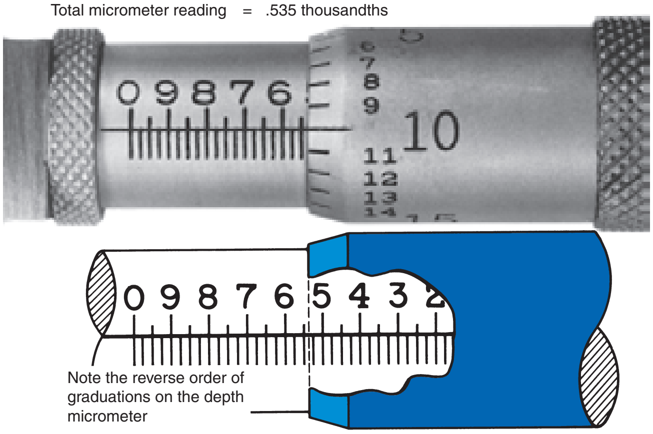


Figure C-144 Sleeve graduations on the depth micrometer are numbered in the direction opposite those on the outside micrometer.

.010 in. Adding these three values results in a total of .535 in., or the amount of extension of the rod from the base.

A depth micrometer **should be tested for accuracy** before it is used. When the 0- to 1-in. rod is used, retract the measuring rod into the base. Clean the base and contact

Figure C-145 Checking a depth micrometer for zero adjustment using the surface plate as a reference surface.

surface of the rod. Hold the micrometer base firmly against a flat, highly finished surface, such as a surface plate, and advance the rod until it contacts the reference surface (Figure C-145). If the micrometer is properly adjusted, it should read zero. When **testing for accuracy** with the **1-in. extension rod**, set the base of the micrometer on a **1-in. gage block** and measure to the reference surface (Figure C-146). Other extension rods can be tested in a like manner.

SELF-TEST

Read and record the five depth micrometer readings in Figures C-147*a* to C-147*e*.

READING METRIC MICROMETERS

The **metric micrometer** (Figure C-148) has a spindle thread with a .5-mm lead. This means that the spindle will move .5 mm when the thimble is turned one complete revolution. Two revolutions of the thimble will advance the spindle 1 mm. In precision machining, metric dimensions are usually expressed in terms of .01 $(\frac{1}{100})$ mm. On the metric micrometer the thimble is graduated into 50 equal divisions, with every fifth division numbered (Figure C-149). If one

Figure C-146 Checking the depth micrometer calibration at the 1.000-in. position in the 0- to 1-in. rod, and a 1-in. square or Hoke gage block.

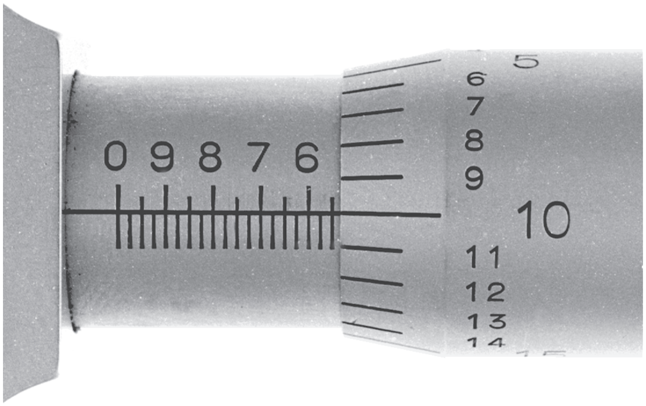


Figure C-147*a*

revolution of the thimble is .5 mm, then each division on the thimble is equal to .5 mm divided by 50, or .01 mm. The sleeve of the metric micrometer is divided into 25 main divisions above the index line, with every fifth division numbered. These are whole-millimeter graduations. Below the index line are graduations that fall halfway between the divisions above the line. The lower graduations represent half, or .5-mm, values. The thimble edge in Figure C-150 leaves the

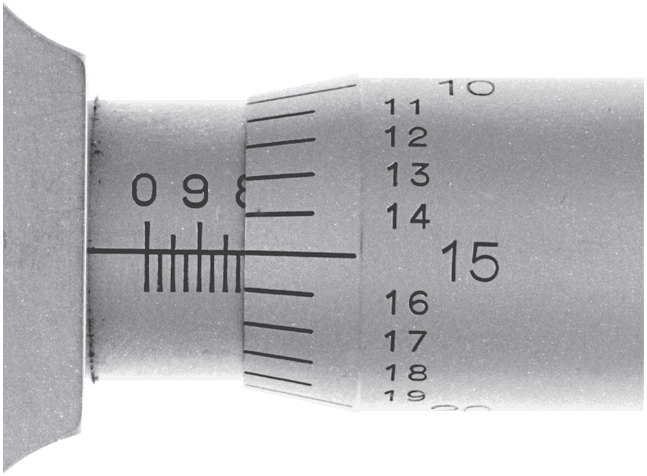


Figure C-147*b*

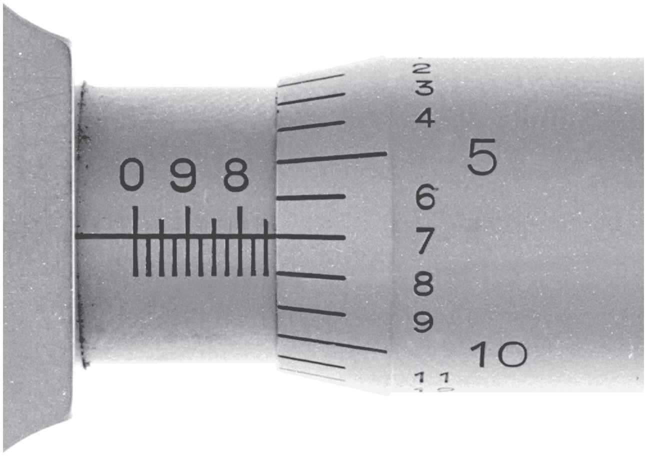


Figure C-147*c*

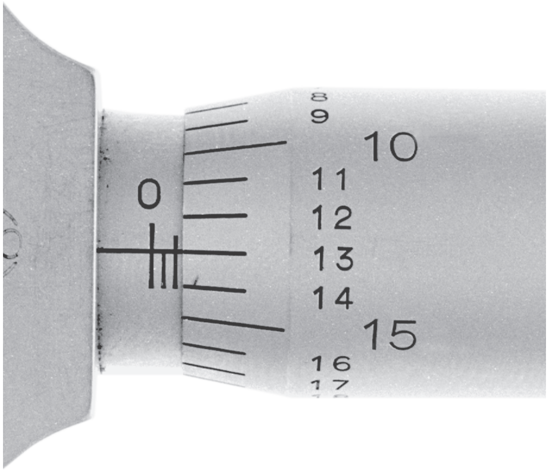


Figure C-147*d*

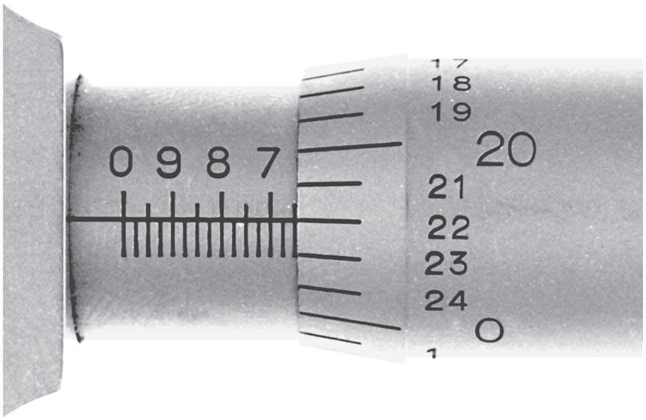
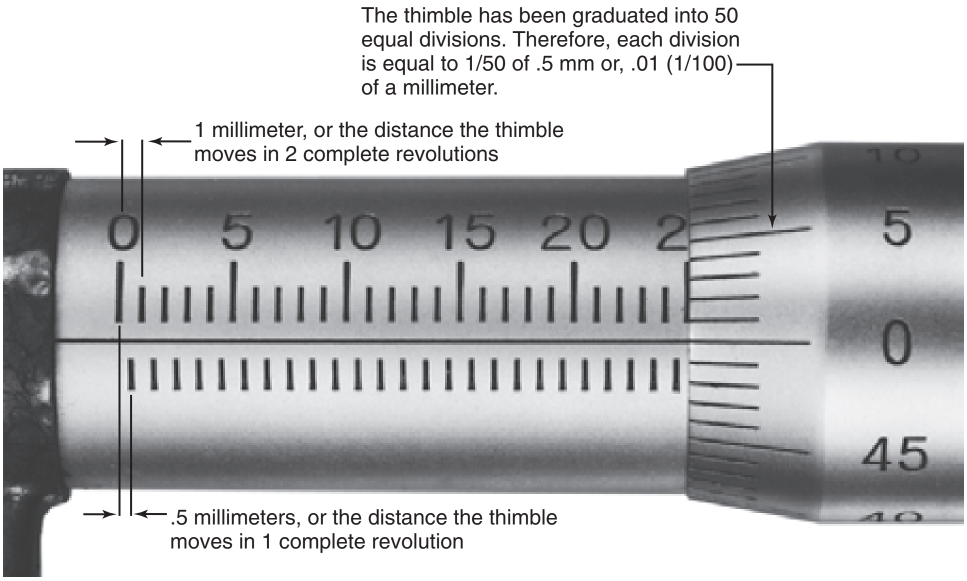


Figure C-147*e*

Figure C-148 Metric micrometer.

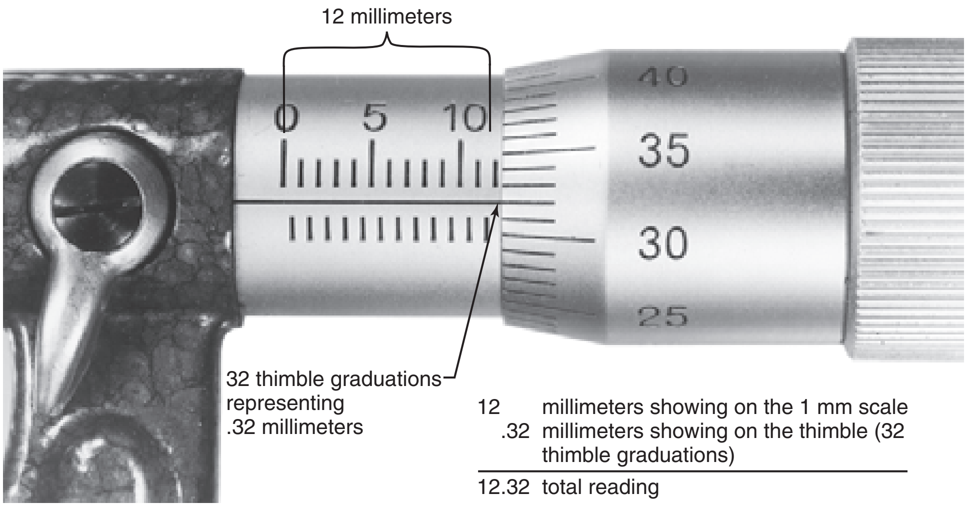


The thimble has been graduated into 50 equal divisions. Therefore, each division is equal to 1/50 of .5 mm or, .01 (1/100) of a millimeter.

1 millimeter, or the distance the thimble moves in 2 complete revolutions

.5 millimeters, or the distance the thimble moves in 1 complete revolution

Figure C-149 Graduations on the metric micrometer.



12 millimeters

32 thimble graduations representing .32 millimeters

12	millimeters showing on the 1 mm scale
.32	millimeters showing on the thimble (32 thimble graduations)
12.32	total reading

Figure C-150 Metric micrometer reading of 12.32 mm.

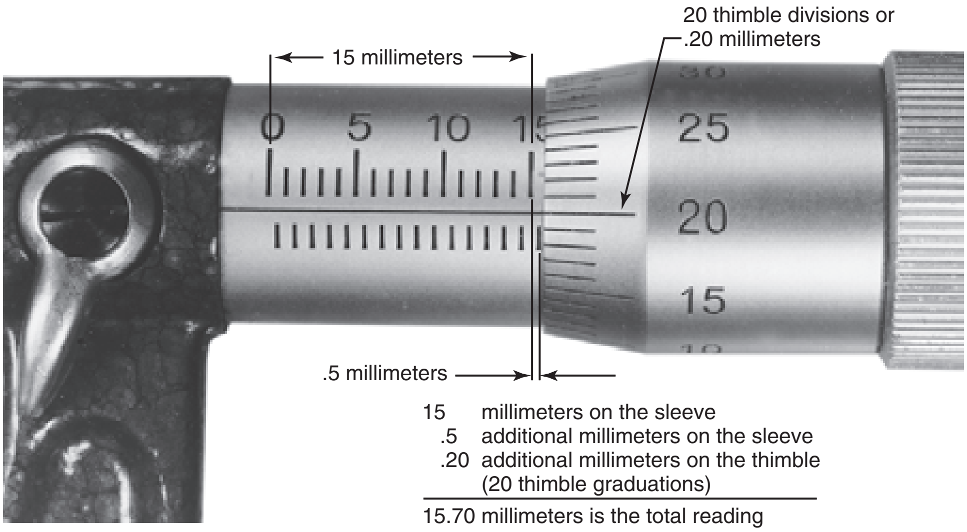


Figure C-151 Metric micrometer reading of 15.70 mm.

12-mm line exposed with no .5-mm line showing. The thimble reading is 32, which is .32 mm. Adding the two figures results in a total of 12.32 mm.

The 15-mm mark in Figure C-151 is exposed on the sleeve plus a .5-mm graduation below the index line. The thimble reads 20 or .20 mm. Adding these three values, 15.00 + .50 + .20, results in a total of 15.70 mm.

Any metric micrometer should receive the same care as that discussed in the section on outside micrometers.

SELF-TEST

Read and record the five metric micrometer readings in Figures C-152*a* to C-152*e*.

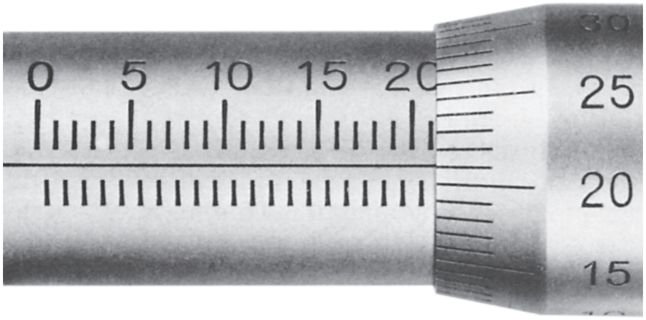


Figure C-152*a*

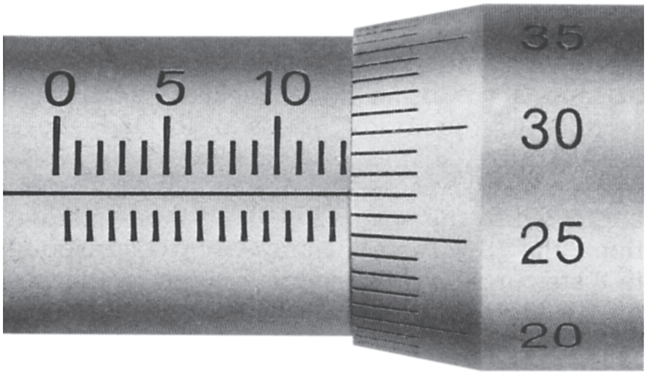


Figure C-152*b*

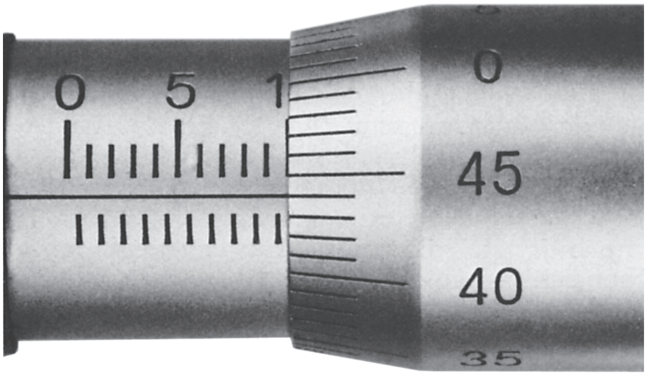


Figure C-152*c*

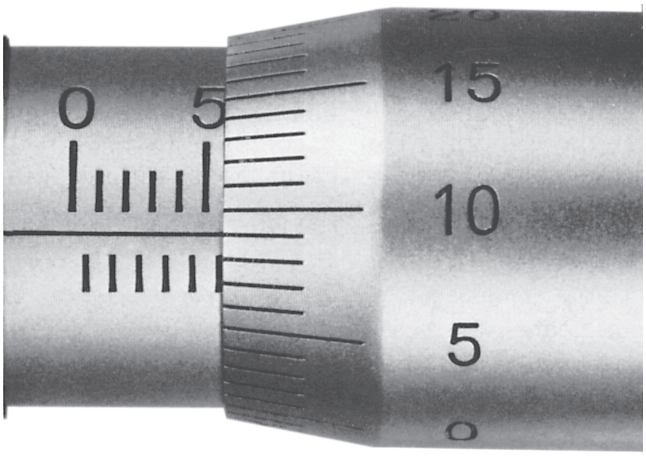


Figure C-152*d*

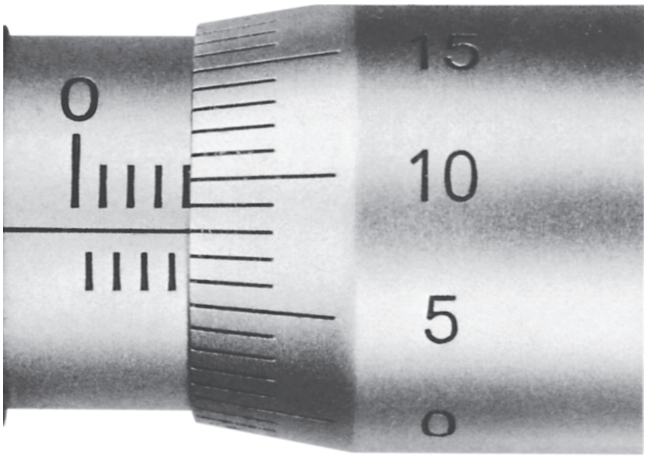


Figure C-152*e*

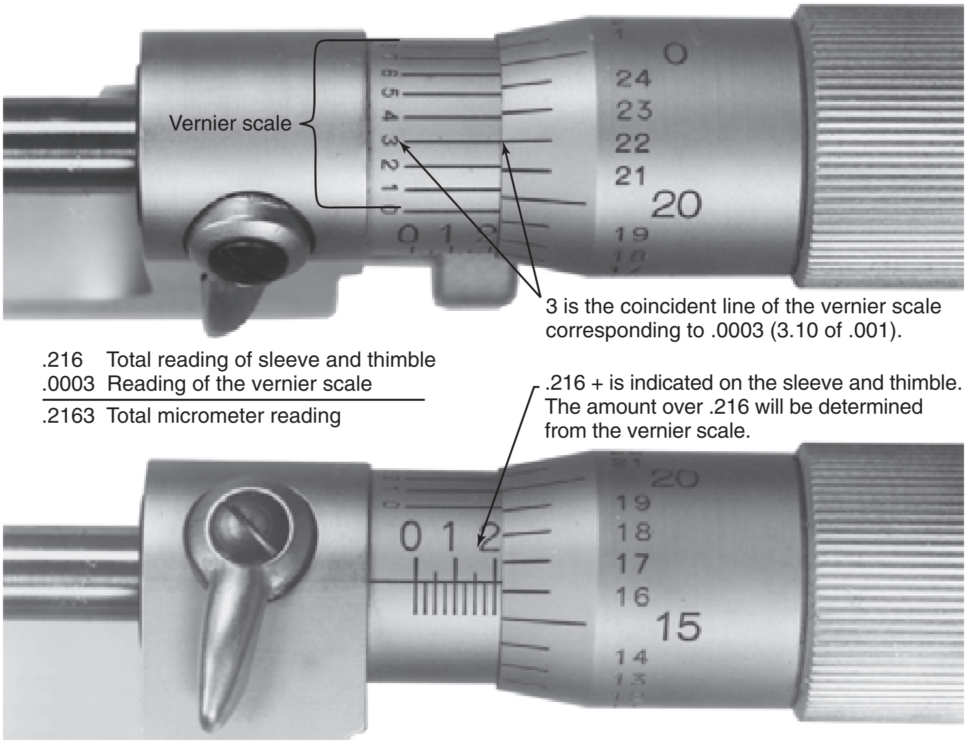


Figure C-153 Inch vernier micrometer reading of .2163 in.

READING VERNIER MICROMETERS

When measurements must be made to a discrimination greater than .001 in., a standard micrometer is not sufficient. With a **vernier micrometer**, readings can be made to a **ten-thousandth part of an inch** (.0001 in.). This kind of micrometer is commonly known as a "tenth mike." A vernier scale is part of the sleeve graduations. The vernier scale consists of 10 lines parallel to the index line and located above it (Figure C-153). The word *tenth* might be a bit misleading. Used in this context, the word *tenth* refers to .0001 in. Do not confuse this with a tenth part of an inch (.10 in.). If the 10 spaces on the vernier scale were compared with the spacing of the thimble graduations, the 10 vernier spacings would correspond to 9 spacings on the thimble. Therefore, the vernier scale spacing must be smaller than the thimble spacing. That is, in fact, precisely the case. Since 10 vernier spacings correspond to 9 thimble spacings, the vernier spacing is $\frac{1}{10}$ smaller than the thimble space. We know that the thimble graduations are .001 in. (one thousandth) apart. Each vernier spacing must then be equal to $\frac{1}{10}$ of .001 in., or .0001 in. (one ten-thousandth). Thus, according to the principle of the vernier, each thousandth of the thimble is subdivided into 10 parts. This permits the vernier micrometer to discriminate to .0001 in.

To read a vernier micrometer, first read to the nearest thousandth as on a standard micrometer. Then, find the line on the vernier scale that coincides with a graduation on the thimble. The value of this coincident vernier scale line is the value in ten-thousandths that must be added to the thousandths reading to make up the total reading. **Remember to add the value of the vernier scale line and not the number of the matching thimble line.**

In the lower view of Figure C-153, a micrometer reading of slightly more than .216 in. is indicated. In the top view, on the vernier scale, the line numbered 3 is in alignment with the line on the thimble. This indicates that .0003 (three ten-thousandths) must be added to the .216 in. for a total reading of .2163. This number is read "two hundred sixteen thousandths and three tenths." (Remember that the three tenths is .0003 in.)

You must exercise cautious judgment when attempting to measure to a tenth of a thousandth using a vernier micrometer. There are many conditions that can influence the reliability of such measurements. The 10 to 1 rule discussed in the section introduction states that for maximum reliability, a measuring instrument must be able to discriminate 10 times finer than the smallest measurement for which it will be used. A vernier micrometer meets this requirement for measurement to the nearest thousandth; however, the instrument lacks the capability to discriminate to one hundred-thousandth, which it should have if it is to be applied in a tenth of a thousandth measurement. This does not mean that a vernier micrometer should not be used for tenth measurement. The modern micrometer is manufactured with this potential in mind. It does mean that the tenth measure should be carried out under **controlled conditions** for truly reliable results. The finish of the workpiece must be extremely smooth. Contact pressure of the measuring faces must be consistent. The workpiece and instrument must be temperature stabilized. Heat transferred to the micrometer by handling can cause it to deviate considerably. Furthermore, the micrometer must be carefully calibrated against a known standard. Only under these conditions can true reliability be realized.

SELF-TEST

Read and record the five vernier micrometer readings in Figures C-154*a* to C-154*e*.

INTERNET REFERENCES

Information on micrometers:

http://www.fvfowler.com

http://mitutoyo.com

http://www.pginc.com

http://www.elexp.com

http://www.auto-met.com

http://www.starrett.com

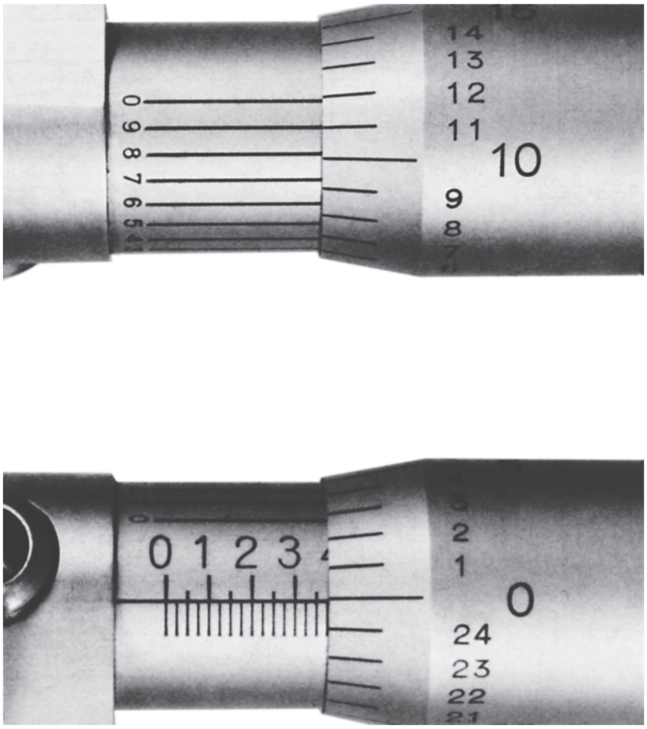


Figure C-154*a*

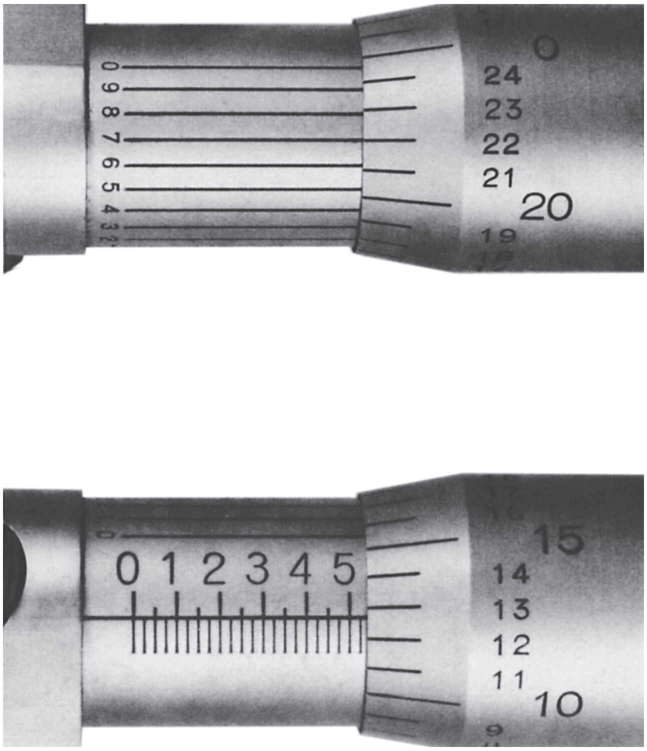


Figure C-154*b*

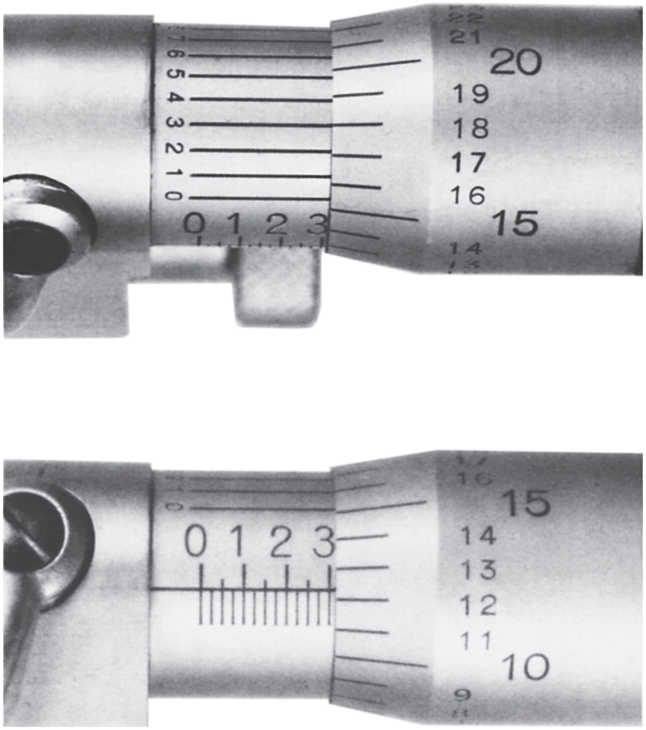


Figure C-154*c*

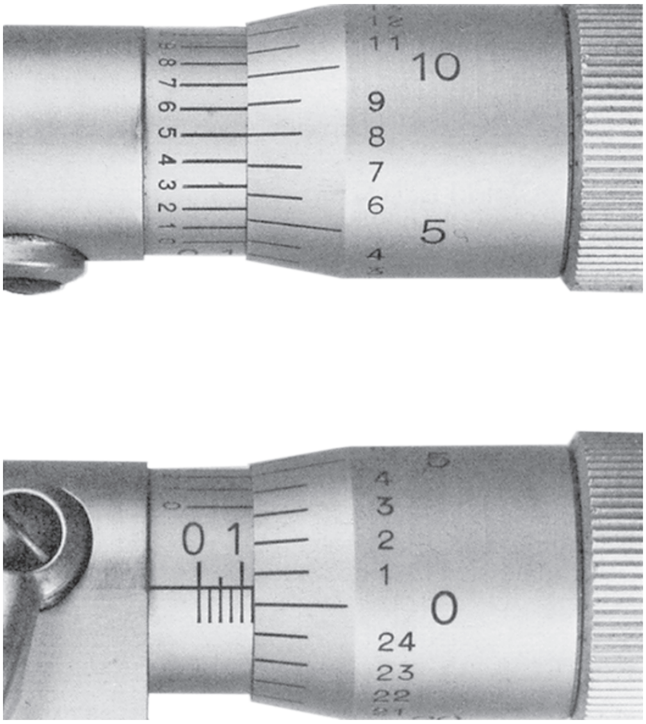


Figure C-154*d*

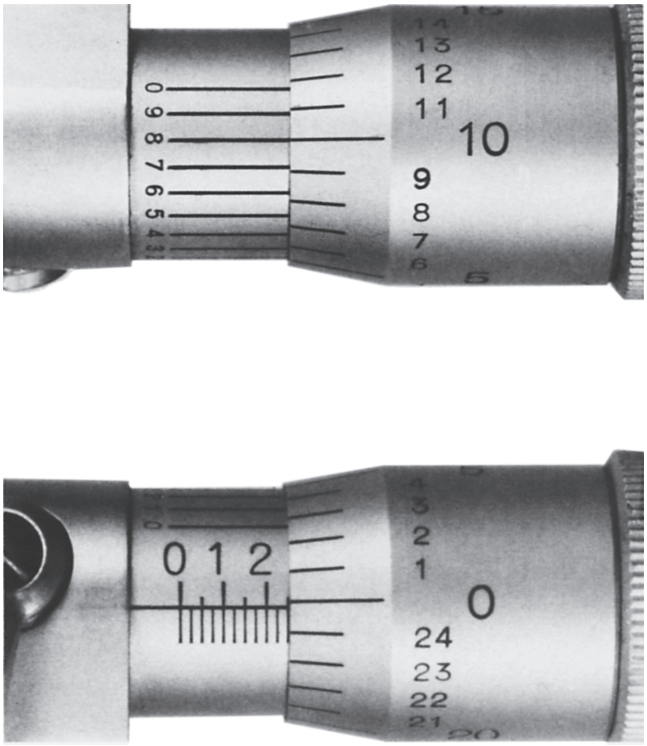


Figure C-154*e*

UNIT FIVE

Using Comparison Measuring Instruments

As a machinist, you will use many measuring instruments that have no inherent capacity to show a measurement. These tools will be used in comparison measurement applications, where they are compared with a known standard, or used in conjunction with an instrument that has the capability of showing a measurement. In this unit you are introduced to the principles of comparison measurement, the common tools of comparison measurement, and their applications.

OBJECTIVES

After completing this unit, you should be able to:

- Define comparison measurement.
- Identify common comparison measuring tools.
- Given a measuring situation, select the proper comparison tool for the measuring requirement.

MEASUREMENT BY COMPARISON

All of us, at some time, have probably been involved in constructing something in which we used no measuring instruments of any kind. For example, suppose that you had to build some wooden shelves. You had the required lumber available, with all boards longer than the shelf spaces. You held a board to the shelf space and marked the required length for cutting. By this procedure, you **compared** the length of the board (**the unknown length**) with the shelf space (**the known length or standard**). After cutting the first board to the marked length, you then used it to determine the lengths of the remaining shelves. The board has no inherent capacity to show a measurement; however, in this case, it became a measuring instrument.

A great deal of comparison measurement often involves the following steps:

1. A device that has no capacity to show measurement is used to establish and represent an unknown dimension.
2. This representation of the unknown is then **transferred** to an instrument that has the capability to show a measurement.

This procedure is commonly known as **transfer measurement**. In the example of cutting shelf boards, the shelf space was transferred to the first board and then the length of the first board was transferred to the remaining boards.

Transfer of measurements may reduce reliability. This factor must be kept in mind when using comparison tools requiring that a transfer be made. Remember that an instrument with the capability to show measurement directly is always best. **Direct-reading instruments should be used whenever possible** in any situation. Measurements requiring a transfer must be accomplished with proper caution if reliability is to be maintained.

COMMON COMPARISON MEASURING TOOLS AND THEIR APPLICATIONS

Spring Calipers

The spring caliper is a common comparison measuring tool for rough measurements of inside and outside dimensions. To use a spring caliper, set one jaw on the workpiece (Figure C-155), use this point as a pivot, and swing the other caliper leg back and forth over the largest point on the diameter. At the same time, adjust the leg spacing. When the correct feel is obtained, remove the caliper and compare it with a steel rule to determine the reading (Figure C-156). The inside spring caliper can be used in a similar manner (Figure C-157). The use of the spring caliper is fading, and it has been replaced by measuring instruments of much higher reliability. The spring caliper should be used only for the roughest of measurements.

Telescoping Gage

The telescoping gage is also a common comparison measuring instrument. Telescoping gages are widely used in the machine shop, and they can accomplish a variety of measuring

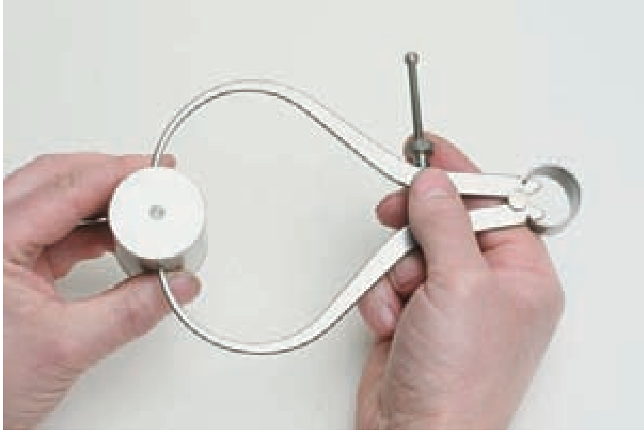


Figure C-155 Set one leg of the caliper against the workpiece.

requirements. The telescoping gage is sometimes called a *snap gage*. This terminology, however, is incorrect. A snap gage is another type of comparison measuring tool, discussed in the introduction to this section.

Telescoping gages generally come in a set of six gages (Figure C-158). The range of the set is usually $\frac{1}{2}$ to 6 in. (12.5 to 150 mm). The gage consists of one or two telescoping plungers with a handle and locking screw. The gage is inserted into a bore or slot, and the plungers are permitted to extend, thus conforming to the size of the feature. The gage is then removed and transferred to a micrometer, where the reading is determined. The telescoping gage can be a reliable and versatile tool if proper procedure is used in its application.

Procedure for Using the Telescoping Gage

Step 1 Select the proper gage for the desired measurement range.

Step 2 Insert the gage into the bore to be measured and release the handle lock screw (Figure C-159). Rock the gage sideways to ensure that you are measuring at the full diameter (Figure C-160). This is especially important in large-diameter bores.

Figure C-156 Comparing the spring caliper with a steel rule.

Figure C-157 Using an inside spring caliper.

Step 3 Lightly tighten the locking screw.

Step 4 Use a downward or upward motion and roll the gage through the bore. The plungers will be pushed in, thus conforming to the bore diameter (Figure C-161). This part of the procedure should be done only once, as rolling the gage back through the bore may cause the plungers to be

Figure C-158 Set of telescoping gages (*Courtesy Terra Community College*).

Figure C-159 Inserting the telescoping gage into the bore (*Courtesy of The L.S. Starrett Co.*).

pushed in farther, resulting in an inaccurate setting. If you feel that the gage is not centered properly, release the locking screw and repeat the procedure from the beginning.

Step 5 Remove the gage and measure with an outside micrometer (Figure C-162). Place the gage between the micrometer spindle and the anvil. Try to determine the same feel on the gage with the micrometer as you felt while the gage was in the bore. Excessive pressure with the micrometer will depress the gage plungers and cause an incorrect reading.

Step 6 Take at least two readings or more with the telescoping gage to verify reliability. If the readings do not agree, repeat steps 2 to 6.

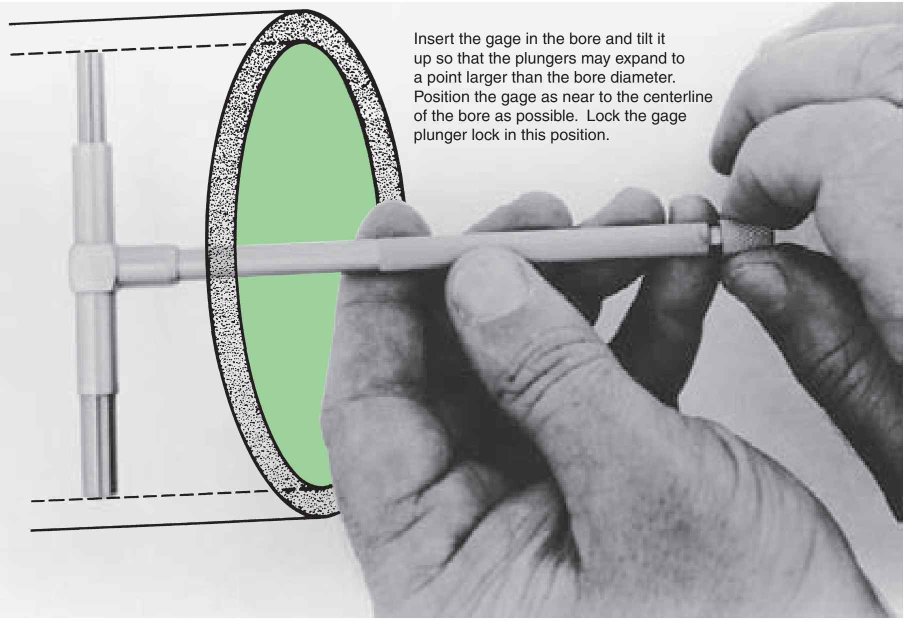
Small Hole Gages

Small hole gages, like telescoping gages, come in sets with a range of $\frac{1}{8}$ to $\frac{1}{2}$ in. (4 to 12 mm). One type of small hole gage consists of a split ball connected to a handle (Figure C-163). A tapered rod is drawn between the split ball halves, causing them to extend and contact the surface to be measured (Figure C-164). The split ball small hole gage has a flattened end so that a shallow hole or slot may be measured. After the gage has been expanded in the feature to be measured, it should be moved back and forth to determine the proper feel. The gage is then removed and measured with an outside micrometer (Figure C-165).

A second type of small hole gage consists of two small balls that can be moved out to contact the surface to be measured. This type of gage is available in a set ranging from $\frac{1}{16}$ to $\frac{1}{2}$ in. (1.5 to 12 mm). Once again, the proper feel must be obtained when using this type of small hole gage (Figure C-166). After the gage is set, it is removed and measured with a micrometer.

Adjustable Parallels

For the purpose of measuring slots, grooves, and keyways, the adjustable parallel may be used. Adjustable parallels are available in sets ranging from about $\frac{3}{8}$ to $2\frac{1}{4}$ in. (10 to 60 mm).



Insert the gage in the bore and tilt it up so that the plungers may expand to a point larger than the bore diameter. Position the gage as near to the centerline of the bore as possible. Lock the gage plunger lock in this position.

Figure C-160 Release the lock and let the plungers expand larger than the bore.

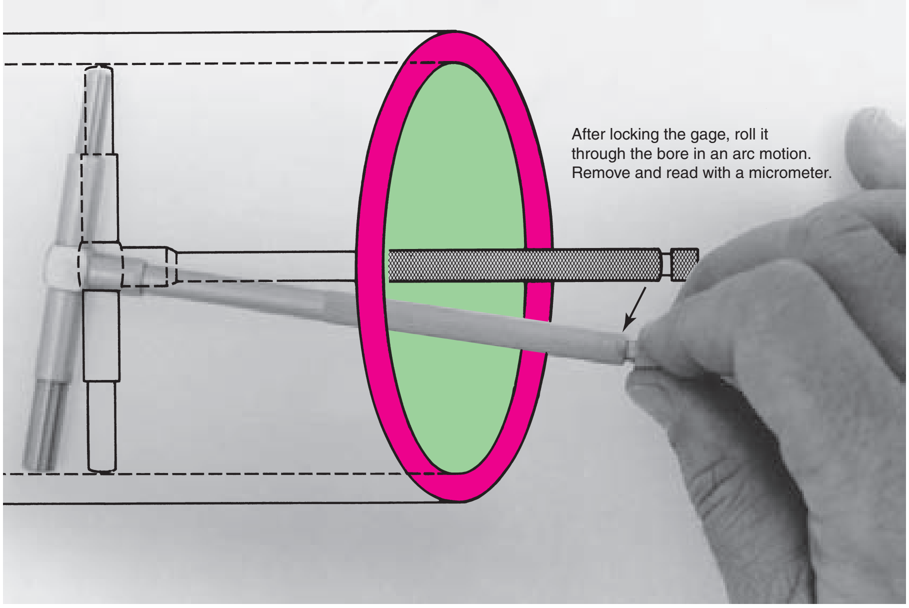


Figure C-161 Tighten the lock and roll the gage through the bore.

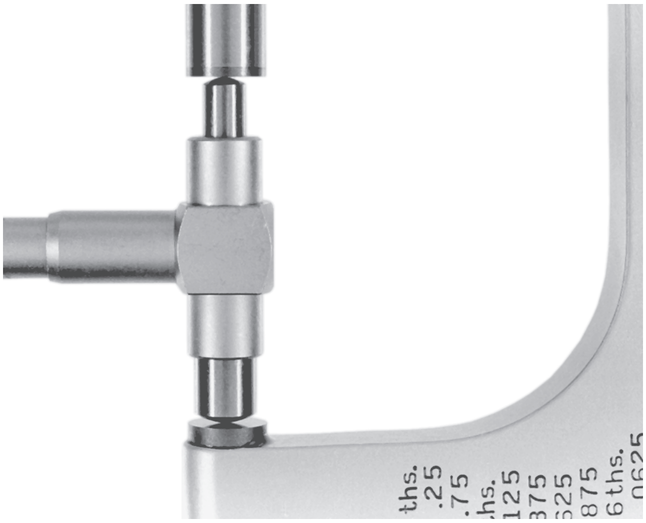


Figure C-162 Checking the telescoping gage with an outside micrometer.

They are precision ground for accuracy. The typical adjustable parallel consists of two parts that slide together on an angle. Adjusting screws are provided so that clearance in the slide may be adjusted or the parallel locked after setting for a measurement. As the halves of the parallel slide, the width increases or decreases depending on direction. The parallel is placed in the groove or slot to be measured and expanded until the parallel edges conform to the width to be measured. The parallel is then locked with a small screwdriver and measured with a micrometer (Figure C-167). If possible, an adjustable parallel should be left in place while being measured.

Figure C-163 Set of small hole gages (*Courtesy of The L.S. Starrett Co.*).

Radius Gages

The typical radius gage set ranges in size from $\frac{1}{32}$ to $\frac{1}{2}$ in. (.8 to 12 mm). Larger radius gages are also available. The gage can be used to measure the radii of grooves and external rounds (outside rounded corners) or internal fillets (inside rounded corners) (Figure C-168). Radius gages are useful for checking the radii of rounds and fillets on castings (Figure C-169).

Thickness Gages

The thickness gage (Figure C-170) is often called a *feeler gage*. It is probably best known for its various automotive applications. However, a machinist may use a thickness gage for such

Figure C-164 Insert the small hole gage in the slot to be measured.

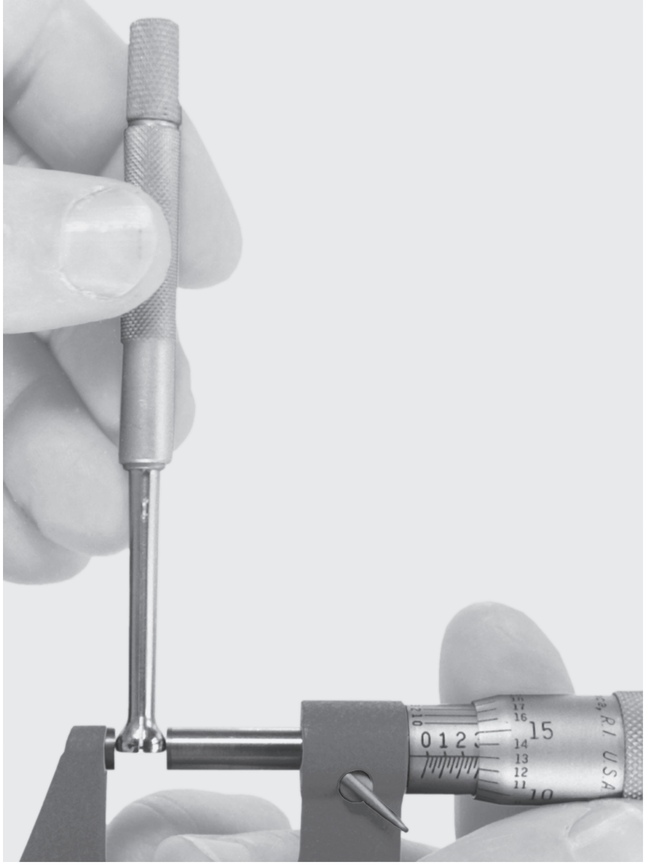


Figure C-165 Withdraw the gage and measure with an outside micrometer.

Figure C-166 Using the twin ball small hole gage.

Figure C-167 Using adjustable parallels.

measurements as the thickness of a shim, setting a grinding wheel above a workpiece, or determining the height difference of two parts. The thickness gage is not a true comparison measuring instrument, as each leaf is marked as to size.

Figure C-168 Using an individual radius gage.

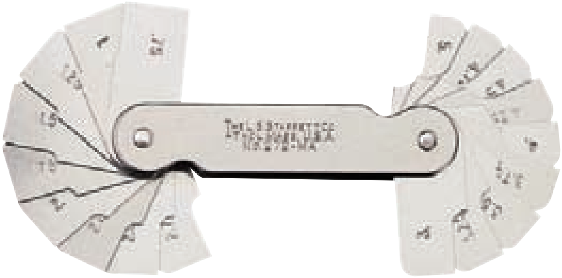


Figure C-169 Radius gage used to check a casting fillet (*Courtesy of The L.S. Starrett Co.*).

However, it is good practice to check a thickness gage with a micrometer, especially when leaves are stacked together.

Planer Gage

The planer gage functions much like an adjustable parallel. Planer gages were originally used to set tool heights on shapers and planers. They can also be used as a comparison measuring tool.

Figure C-170 Using a feeler or thickness gage (*Courtesy of The L.S. Starrett Co.*).

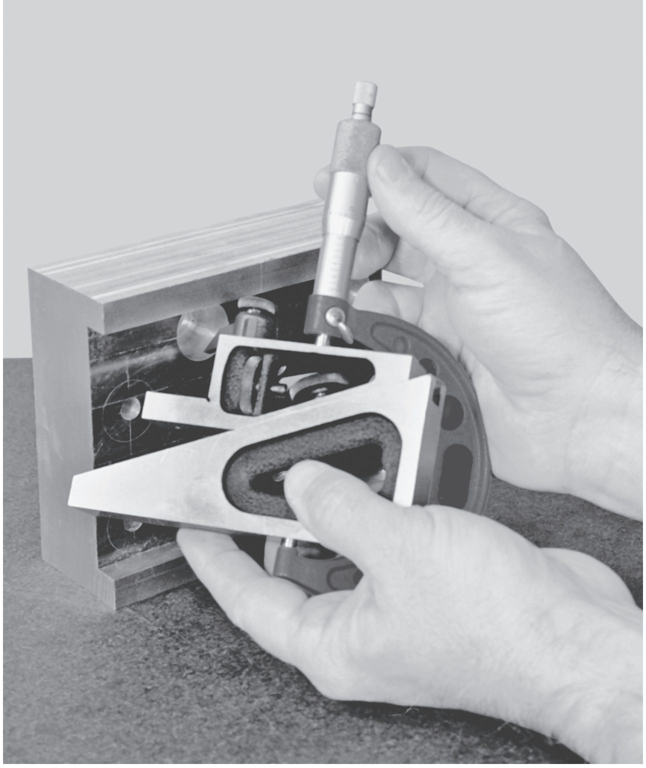


Figure C-171 Setting the planer gage with an outside micrometer.

The planer gage may be equipped with a scriber and used in layout. The gage may be set with a micrometer (Figure C-171) or in combination with a dial test indicator and gage blocks. In this application, the planer gage is set by using a test indicator set to zero on a gage block (Figure C-172). This dimension is then transferred to the planer gage (Figure C-173). After the gage has been set,

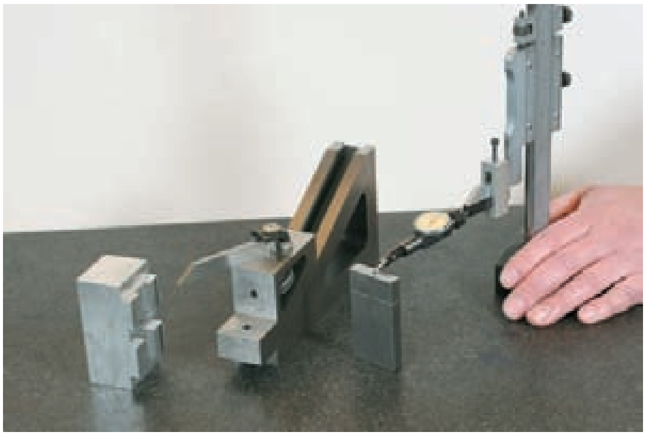


Figure C-172 Setting the dial test indicator to a gage block.

with the scriber attached, the instrument is used in a layout application (Figure C-174).

Squares

The square is an important and useful tool for the machinist. A square is a comparative measuring instrument in that it is used to compare its degree of perpendicularity with an unknown degree of perpendicularity on the workpiece. You will use several common types of squares.

Machinist's Combination Square

The combination square (Figure C-175) is part of the combination set (Figure C-176). The combination set consists of a graduated rule, square head, bevel protractor, and center head. The square head slides on the graduated rule and can be locked at any position (Figure C-177). This feature makes the tool useful for layout, as the square head can be set according to the rule graduations. The combination square head also has a 45-degree angle along with a spirit level and layout scriber. The combination set is one of the most versatile tools of the machinist.

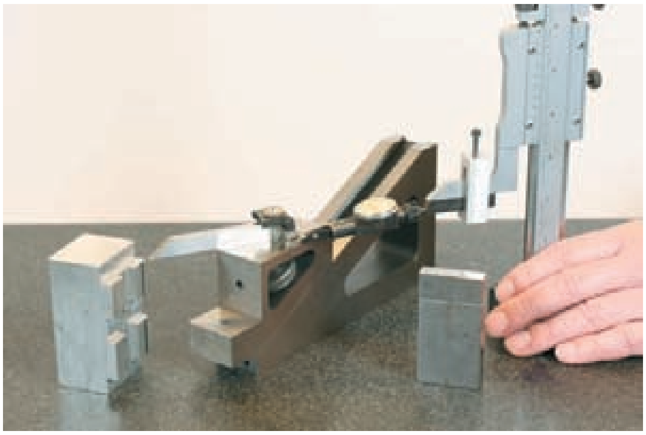


Figure C-173 Transferring the measurement to the planer gage.

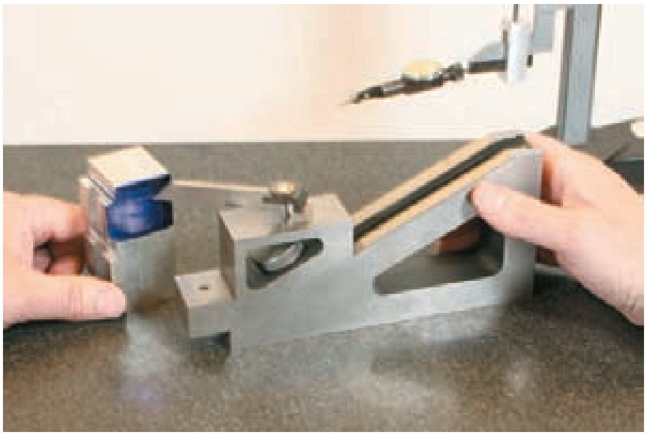


Figure C-174 Using the planer gage in layout.

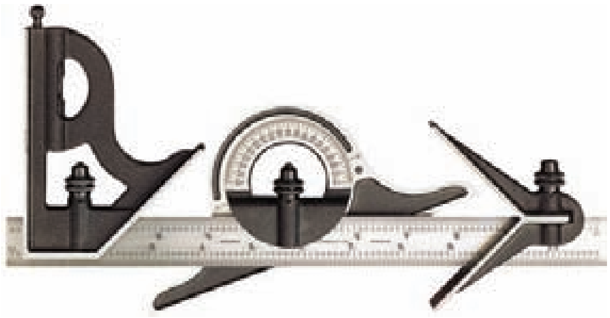


Figure C-175 Combination square head with scriber (*Courtesy of The L.S. Starrett Co.*).

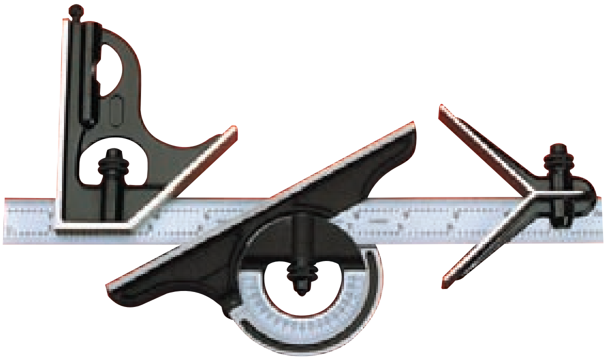


Figure C-176 Machinist's combination set (*Courtesy of The L.S. Starrett Co.*).

Solid Beam Square

On the solid beam square, the beam and blade are fixed. Solid beam squares range in size from 2 to 72 in. (Figure C-178).

Precision Beveled Edge Square

The precision beveled edge square is an extremely accurate square used in the

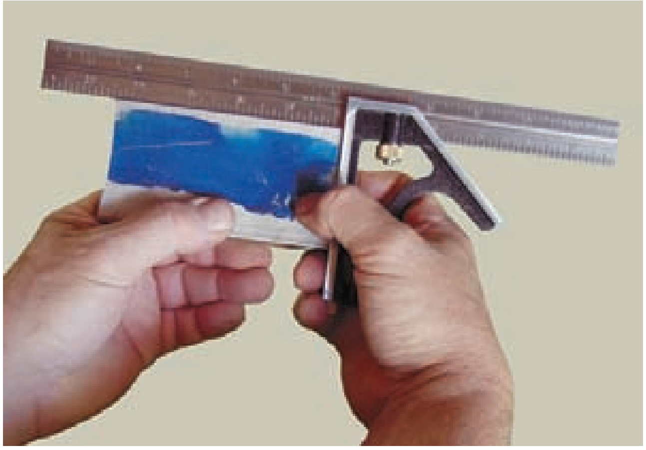


Figure C-177 Using the combination square.

Figure C-179 Precision beveled-edge square (*Courtesy of The L.S. Starrett Co.*).

toolroom and in inspection applications. The beveled edge permits a single line of contact with the part to be checked. Precision squares range in size from 2 to 14 in. (Figure C-179).

The squares discussed up to this point have no capacity to directly indicate the amount of deviation from perpendicularity. The only determination that can be made is that the workpiece is perpendicular or not by comparison with the square. The actual amount of deviation from perpendicularity on the workpiece must be determined by other measurements. With the following group of squares, the deviation from perpendicularity can be measured directly. In this respect, the following instruments are not true comparison tools, since they can show a measurement directly.

Cylindrical Square The direct-reading cylindrical square (Figure C-180) consists of an accurate cylinder with one end square to the axis of the cylinder. The other end is made slightly out of square with the cylindrical axis. When the nonsquare end is placed on a clean surface plate, the instrument is actually tilted slightly. As the square is rotated (Figure C-181), one point on the circumference of the cylinder will eventually come into perpendicularity with the surface plate. On a cylindrical square, this point is marked by a vertical line running the full length of the tool. The cylindrical square has a set of curved lines marked on the cylinder that permits deviation from squareness of the workpiece to be determined. Each curved line represents a deviation of .0002 of an inch over the length of the instrument.

Cylindrical squares are applied in the following manner. The square is placed on a clean surface plate and brought into contact with the part to be checked. The square is then rotated until contact is made over the entire length of the instrument. The deviation from squareness is determined by reading the amount corresponding to the line on the square that is

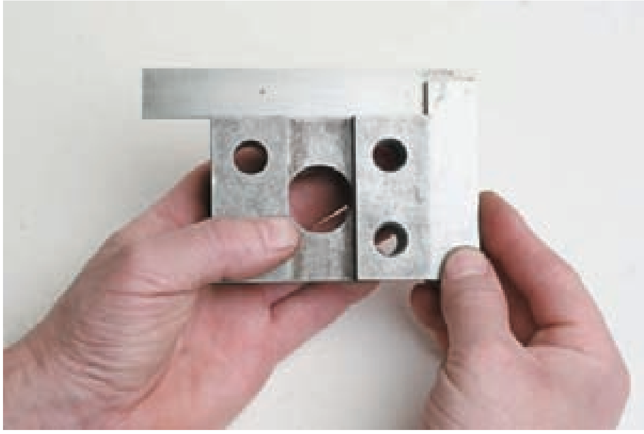


Figure C-178 Solid beam square.

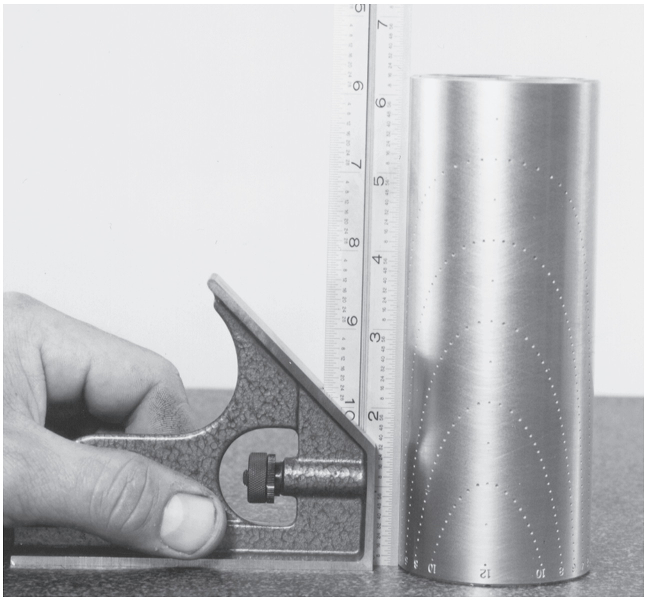
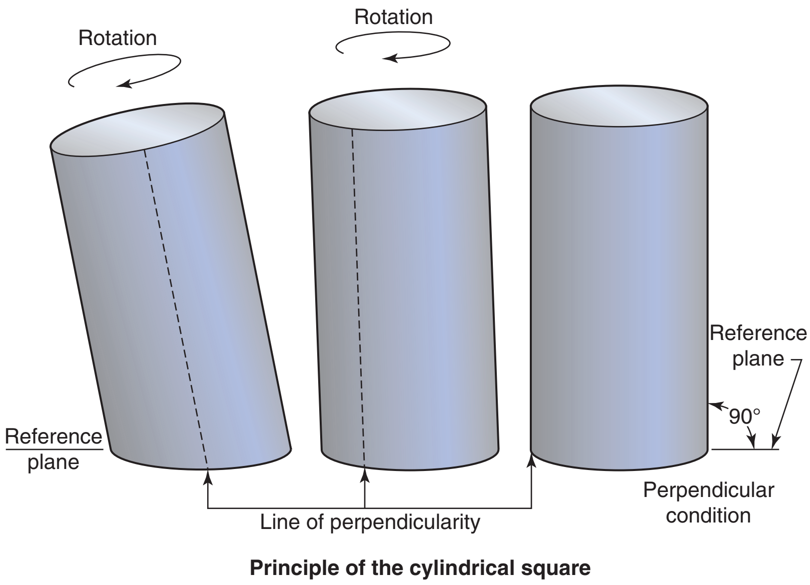


Figure C-180 Cylindrical square.

Figure C-181 Principle of the cylindrical square.



in contact with the workpiece. Cylindrical squares are often used to check the accuracy of another square (Figure C-180). When the instrument is used on its square end, it may be applied as a plain square. Cylindrical squares range in size from 4 to 12 in.

Diemaker's Square The diemaker's square (Figure C-182) is used in such applications as checking clearance angle on a die (Figure C-183). The instrument can be used with a straight or offset blade. A diemaker's square can be used to measure a deviation of 10 degrees on either side of the perpendicular.

Micrometer Square The micrometer square (Figure C-184) is another type of adjustable square. The blade is tilted by means of a micrometer adjustment to determine the deviation of the part being checked.

Figure C-182 Diemaker's square.

The square is one of the few measurement tools that is essentially self-checking. If you have a workpiece with true parallel sides, as measured with a micrometer, one end can be observed under the beam of the square and the error observed. Then, the part can be rotated under the beam 180 degrees and rechecked. If the error is identical but reversed, the square is accurate. If there is a difference, except for simple reversal, the square should be considered inaccurate. It should be checked against a standard, such as a cylindrical square.

Figure C-183 Using the diemaker's square to check die clearance angle.

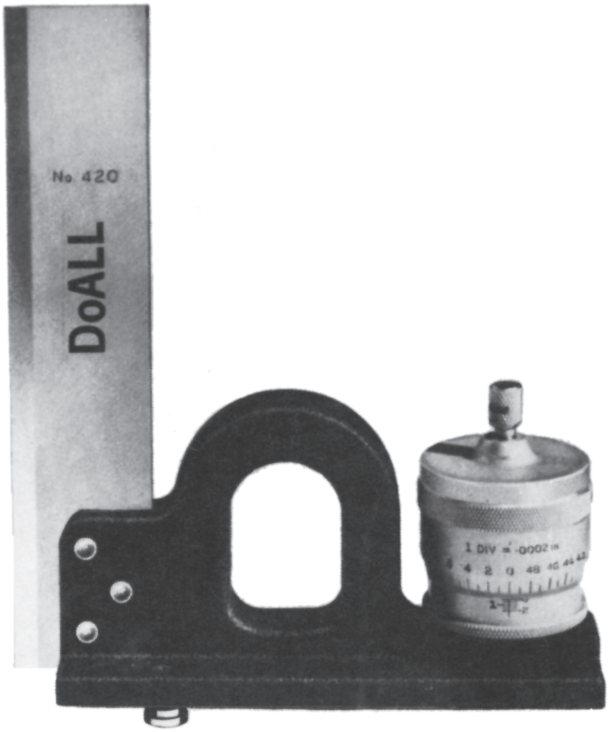


Figure C-184 Micrometer square (*Courtesy of the DoALL Company*).

Indicators

The many types of indicators are some of the most valuable and useful tools for the machinist. There are two general types of indicators in general use, namely, **dial indicators** and **dial test indicators**. Both types generally take the form of a spring loaded spindle that when depressed actuates the hand of an indicating dial. At the initial examination of a dial or test indicator, you will note that the dial face is usually graduated in thousandths of an inch or subdivisions of thousandths. This might lead you to the conclusion that the indicator spindle movement corresponds directly to the amount shown on the indicator face. However, this conclusion is to be arrived at only with the most cautious judgment. **Dial test indicators should not be used to make direct linear measurements**. Reasons for this will be developed in the information to follow. Dial indicators can be used to make linear measurements, but only if they are specifically designed to do so and under proper conditions.

As a machinist, you will use dial and test indicators almost daily in the machine shop. Indicators are essential to the accurate completion of your job. However, do not ask that an indicator do what it was not designed to do. Dial and test indicators when properly used are invaluable tools.

Dial Indicators Discriminations of dial indicators typically range from .00005 to .001 in. In metric dial indicators, the discriminations typically range from .002 to .01 mm. Indicator ranges, or the total reading capacity of the instrument, may commonly range from .003 to 2.000 in., or .2 to 50 mm for metric instruments. On the **balanced** indicator (Figure C-185), the face numbering goes both clockwise and counterclockwise from zero. This is convenient for comparator applications where readings above and below zero need to be indicated. The indicator shown has a lever-actuated stem. This permits the stem to be retracted away from the workpiece if desired.

The continuous reading indicator (Figure C-186) is numbered from zero in one direction. This indicator has a discrimination of .0005 in. and a total range of 1 in. The small center hand counts revolutions of the large hand. Note that the center dial counts each .100 in. of spindle travel. This indicator is also equipped with **tolerance hands** that can be set to mark a desired limit. Many dial indicators are designed for high discrimination and short range (Figure C-187). This indicator has a .0001-in. discrimination and a range of .025 in.

The **back plunger** indicator (Figure C-188) has the spindle in the back or at right angles to the face. This type of indicator usually has a range of about .200 in. with .001-in. discrimination. It is a popular model for use on a machine tool. The indicator usually comes with mounting accessories (Figure C-188).

Indicators are equipped with a **rotating face** or **bezel.** This feature permits the instrument also to have a **bezel lock**. Dial indicators may have removable spindle tips, thus permitting use of different-shaped tips as required by the specific application (Figure C-189).

Figure C-185 Balanced dial indicator.

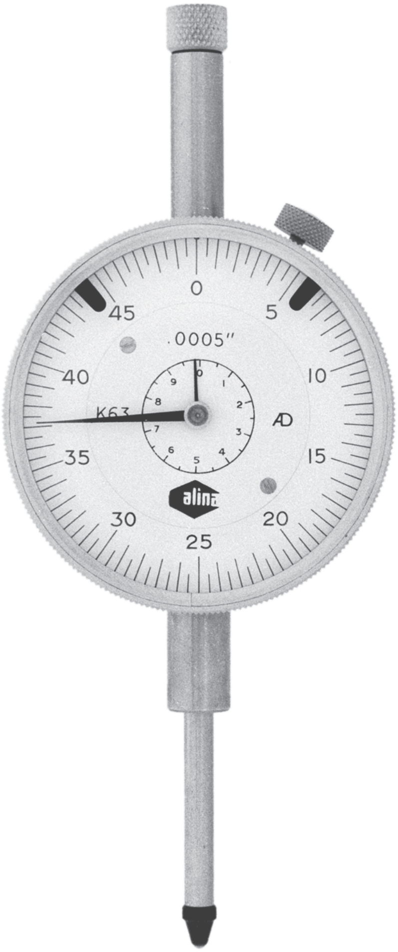


Figure C-186 Dial indicator with 1 in. of travel.

Figure C-187 Dial indicator with .025-in. range and .0001-in. discrimination.

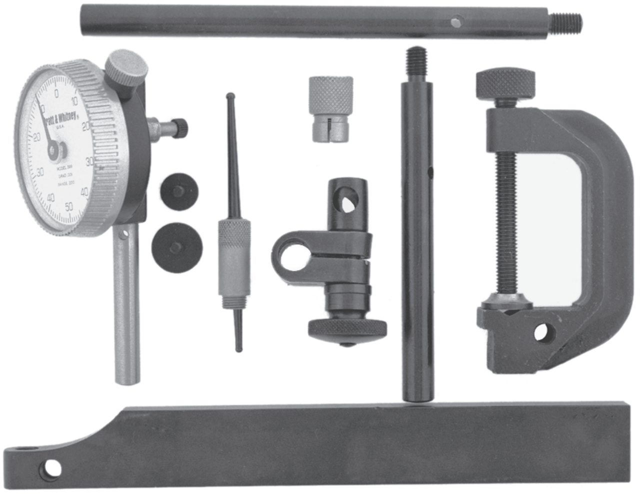


Figure C-188 Back plunger indicator with mounting accessories.

Figure C-189 Dial indicator tips with holder (*Courtesy Rank Scherr–Tumico, Inc.*).

Care and Use of Indicators Dial indicators are precision instruments and should be treated accordingly. They **must not be dropped** and should **not be exposed to severe shocks**. Dropping an indicator may bend the spindle and render the instrument useless. Shocks, such as hammering on a workpiece while an indicator is still in contact, may damage the delicate operating mechanism. The spindle should be kept free from dirt and grit, which can cause binding that results in damage and false readings. It is important to **check** indicators **for free travel** before using. When an indicator is not in use, it should be stored carefully with a protective device around the spindle.

One problem encountered by indicator users is **indicator mounting**. All indicators must be **mounted solidly** to be reliable. Indicators must be clamped or mounted securely when used on a machine tool. Various mounting devices are in common use. Some have magnetic bases that permit an indicator to be attached at any convenient place on a machine tool. The permanent-magnet indicator base (Figure C-190) is a useful accessory. This type of indicator

Figure C-190 Permanent-magnet indicator base (*Courtesy of the L.S. Starrett Co.*).

base is equipped with an adjusting screw that can be used to set the instrument to zero. Another useful magnetic base has a provision for turning off the magnet by mechanical means (Figure C-191). This feature makes for easy locating of the base prior to turning on the magnet. Bases that make use of flexible-link indicator holding arms are also in general use. Often, they are not adequately rigid for reliability. In addition to being held on a magnetic base, an indicator may be clamped to a machine setup by the use of any suitable clamps.

Figure C-191 Magnetic-base indicator holder with on/off magnet (*Courtesy of The L.S. Starrett Co.*).

Dial Test Indicators Dial test indicators frequently have a discrimination of .0005 in. and a range of about .030 in. The test indicator is frequently quite small (Figure C-192) so that it can be used to indicate in locations inaccessible to other indicators. The spindle or tip of the test indicator can be swiveled to any desired position. Test indicators are usually equipped with a **movement reversing lever**. This means that the indicator can be actuated by pressure from either side of the tip. The instrument need not be turned around. Test indicators, like dial indicators, have a rotating bezel for zero setting. Dial faces are generally of the balanced design. The same care given to dial indicators should be extended to test indicators.

Potential for Error in Using Dial Indicators Indicators must be used with appropriate caution for reliable results. The spindle of a dial indicator usually consists of a gear rack that engages a pinion and other gears that drive the indicating hand. In any mechanical device, there is always clearance between the moving parts. There are also minute errors in

Figure C-192 Dial test indicator.

the machining of the indicator parts. Consequently, small errors may creep into an indicator reading. This is especially true in long-travel indicators. For example, if a 1-in.-travel indicator with a .001-in. discrimination has plus or minus 1 percent error at full travel, the following condition could exist if the instrument was to be used for a direct measurement: You wish to determine if a certain part is within the tolerance of .750 ± .003 in. The 1-in.-travel indicator has the capacity for this measurement, but remember that it is accurate only to plus or minus 1 percent of full travel. Therefore, .01 × 1.000 in. is equal to ±.010 in., or the total possible error. To calculate the error per thousandth of indicator travel, divide .010 in. by 1000. This is equal to .00001 in., which is the average error per thousandth of indicator travel. This means that at a travel amount of .750 in., the indicator error could be as much as .00001 in. × 750, or ±.0075 in. In a direct measurement of the part, the indicator could read anywhere from .7425 to .7575. As you can see, this is well outside the part tolerance and would hardly be reliable (Figure C-193).

The indicator should be used as a comparison measuring instrument by the following procedure (Figure C-193). The indicator is set to zero on a .750-in. gage block. The part to be measured is then placed under the indicator spindle. In this case, the error caused by a large amount of indicator travel is greatly reduced, because the travel is never greater than the greatest deviation of a part from the basic size. The total part tolerance is .006 in. (±.003 in.). Therefore, 6 × .00001 in. error per thousandth is equal to only ±.00006 in. This is well within the part tolerance and, in fact, cannot even be read on a .001-in discrimination indicator.

Of course, you will not know the amount of error on any specific indicator. This can be determined only by a calibration procedure. Furthermore, you would probably not use a long-travel indicator in this particular application. A moderate- to short-travel indicator would be more appropriate. Keep in mind that any indicator may contain some **travel error** and that by using a fraction of that travel, the amount of this error can be reduced considerably.

In the introduction to this section you learned that the axis of a linear measurement instrument must be in line with the axis of measurement. If a dial indicator is misaligned with the axis of measurement, the following condition will exist: In Figure C-194 line *AC* represents the axis of measurement, and line *AB* represents the axis of the dial indicator. If the distance from *A* to *C* is .100 in., then the distance from *A* to *B* is obviously longer, since it is the hypotenuse of triangle *ABC*. The angle of misalignment, angle *A*, is equal to 20 degrees. The distance from *A* to *B* can then be calculated by the following:

$$AB = \frac{.100}{\cos A}$$

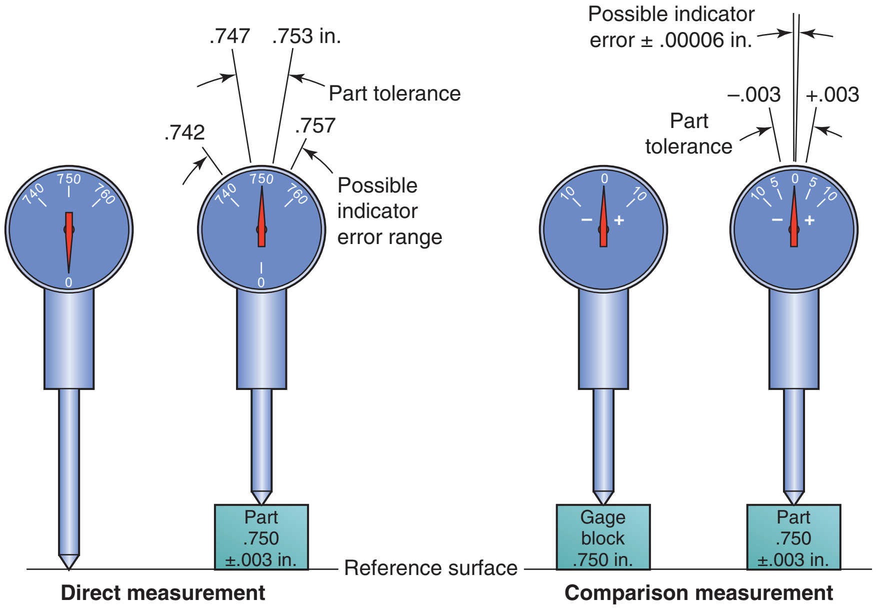
$$AB = \frac{.100}{.9396}$$

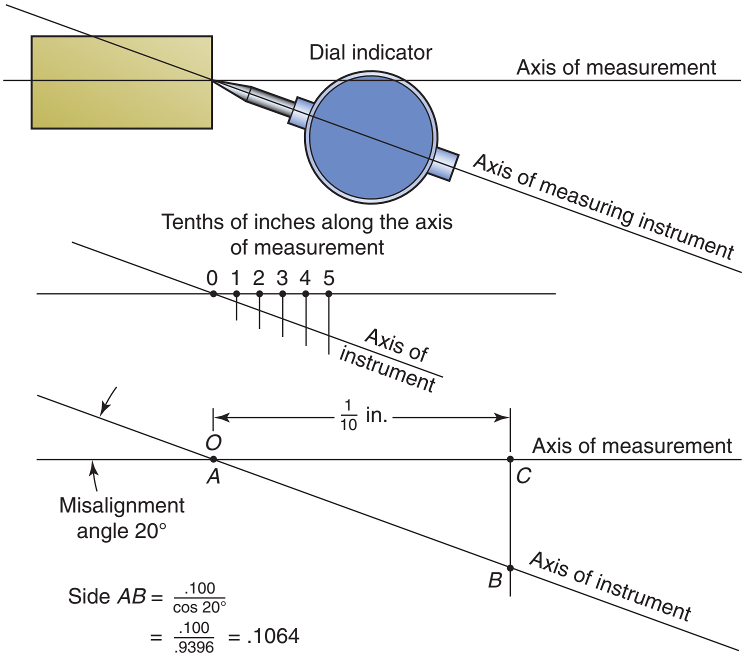
$$AB = .1064 \text{ in.}$$

This shows that a movement along the axis of measurement results in a much larger movement along the instrument axis. This **error** is known as **cosine error** and must be kept in mind when using dial indicators. Cosine error increases as the angle of misalignment increases.

When using dial test indicators, watch for **arc versus chord length errors** (Figure C-195). The tip of the test indicator moves through an arc. This distance may be considerably greater than the chord distance of the measurement axis. Dial test indicators should **not** be used to make direct measurements. They should be applied only in comparison applications.

Figure C-193 Potential for errors in indicator travel.





A movement of .100 along the axis of measurement results in a movement of .1064 along the axis of the measuring instrument.

Figure C-194 Cosine error.

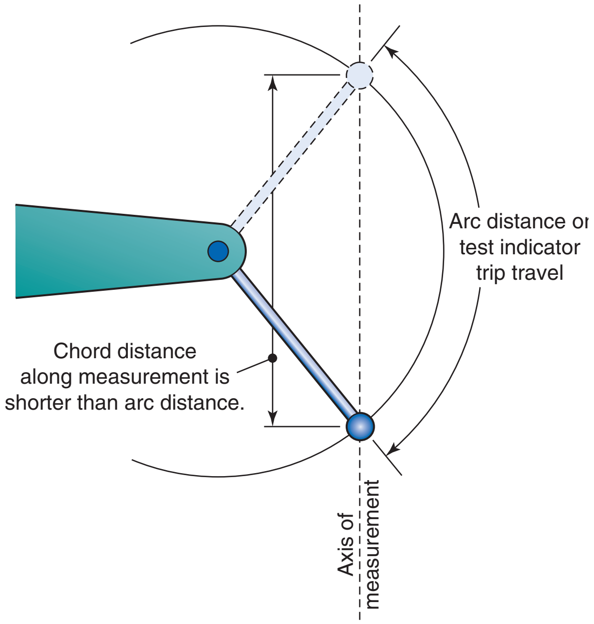


Figure C-195 Potential for error in dial test indicator tip movement.

USING DIAL TEST INDICATORS IN COMPARISON MEASUREMENTS

The dial test indicator is very useful in making comparison measurements in conjunction with the height gage and height transfer micrometer. Comparison measurement using a vernier height gage is made as follows:

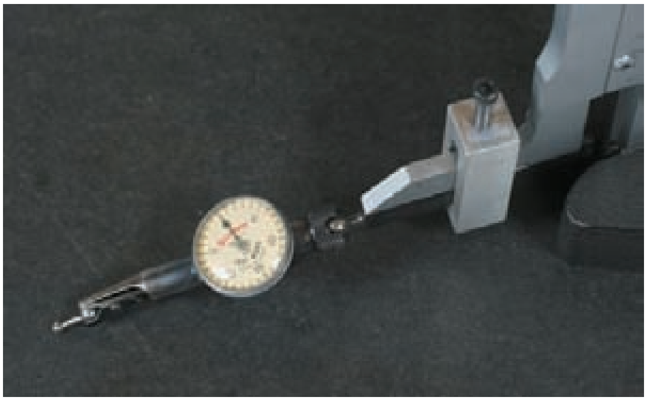


Figure C-196 Setting the dial test indicator to zero on the reference surface.

Step 1 Set the height gage to zero and adjust the test indicator until it also reads zero when in contact with the surface plate (Figure C-196). It is important to use a test indicator for this procedure. Using a scriber tip on a height gage is an inferior way to attempt measurements and can lead to substantial error.

Step 2 Raise the indicator and adjust the height gage vernier until the indicator reads zero on the workpiece (Figure C-197). Read the dimension from the height scale.

Comparison measurement can also be made using a precision height gage (Figure C-198). The precision height gage shown consists of a series of rings moved by the micrometer spindle. The ring spacing is an accurate 1 in., and the micrometer head has a 1-in. travel. Other designs use projecting gage blocks at inch intervals or other types of measuring steps. Discrimination of the typical height micrometer is .0001 in. (Figure C-199). Precision height gages come in various height capacities and sometimes have

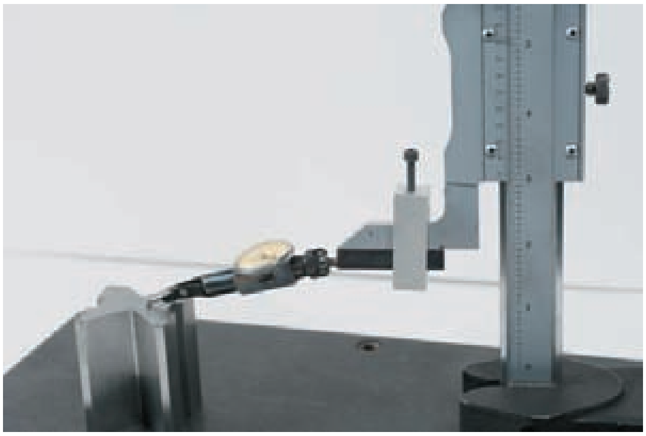


Figure C-197 Using the dial test indicator and vernier height gage to measure the workpiece.

Figure C-198 Precision height gage.

riser blocks as accessories. In Figure C-200, a planer gage is being set using the test indicator and height micrometer. The following procedure is used:

Step 1 The height transfer micrometer is adjusted to the desired height setting. The test indicator is zeroed on the appropriate ring (Figure C-200). A height transfer gage, vernier height gage, or other suitable means can be used to hold the indicator.

Figure C-199 Reading the precision height gage.

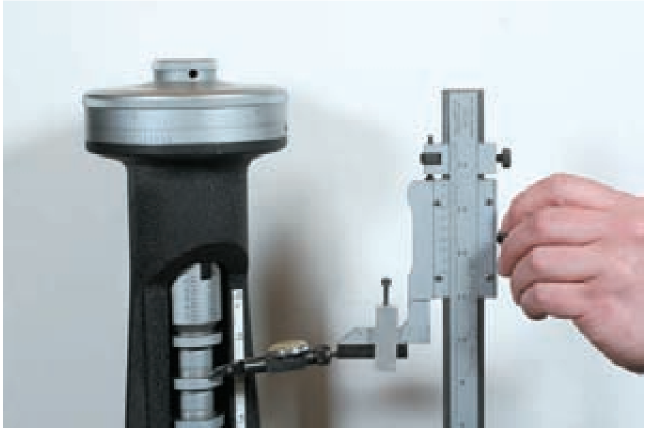


Figure C-200 Setting the dial test indicator to the precision height gage.

Step 2 The indicator is then moved over to the planer gage, which is adjusted until the test indicator reads zero (Figure C-201).

Figure C-201 Transferring the measurement to the planer gage.

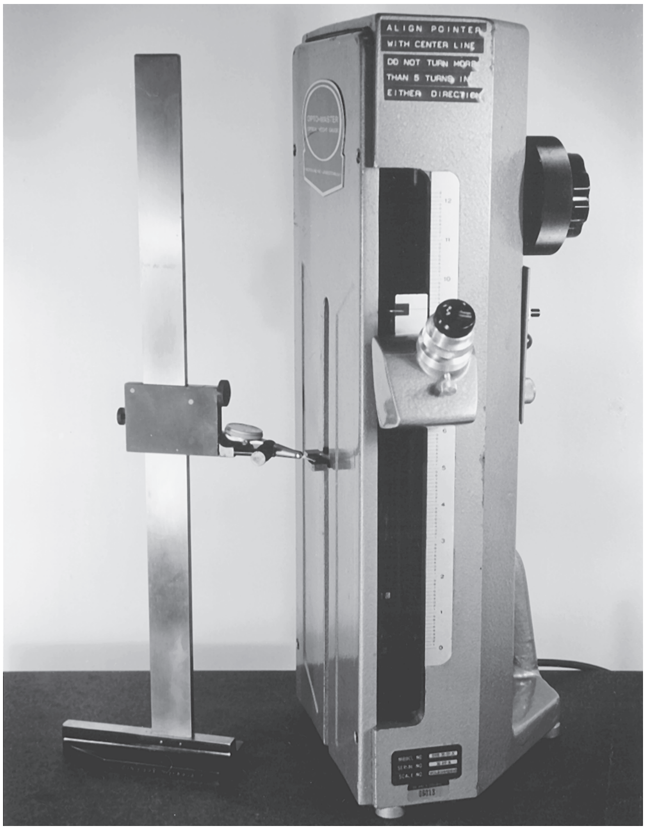


Figure C-202 Setting the dial test indicator using the optical height gage.

Figure C-203 Electronic digital height gage (*Mitutoyo America Corp.*).

Test indicators can also be used to make comparison measurements in conjunction with an optical height gage (Figure C-202). Digital electronic height gages are also available (Figure C-203).

Comparators

Comparators are exactly what their name implies: They are instruments that compare the size or shape of the workpiece with a known standard. Types include dial indicator, optical, electrical, and electronic comparators. Comparators are used when parts must be checked to determine acceptable tolerance. They may also be used to check the geometry of such things as threads, gears, and formed machine tool cutters. The electronic comparator may be found in the inspection area, toolroom, or gage laboratory and used in routine inspection and calibration of measuring tools and gages.

Dial Indicator Comparators The dial indicator comparator is no more than a dial indicator attached to a rigid stand (Figure C-204). These are dial indicator instruments such as the ones previously discussed; however, because of their application as comparator instruments, as many errors as possible have been eliminated by the fixed design of the instrument's components. The indicator is set to zero at the desired dimension by use of gage blocks (Figure C-205). When using a dial indicator comparator, keep in mind the

potential for error in indicator travel and instrument alignment along the axis of measurement. Once the indicator has been set to zero, parts can be checked for acceptable tolerance (Figure C-206). A particularly useful comparator indicator for this is one equipped with tolerance hands (Figure C-207). The tolerance hands can be set to establish an upper and lower limit for part size. On this type of comparator indicator, the spindle can be lifted clear of the workpiece by using the cable mechanism. This permits the indicator to always travel downward as it comes into contact with the work. This is an additional compensation for any mechanical error in the indicator mechanism.

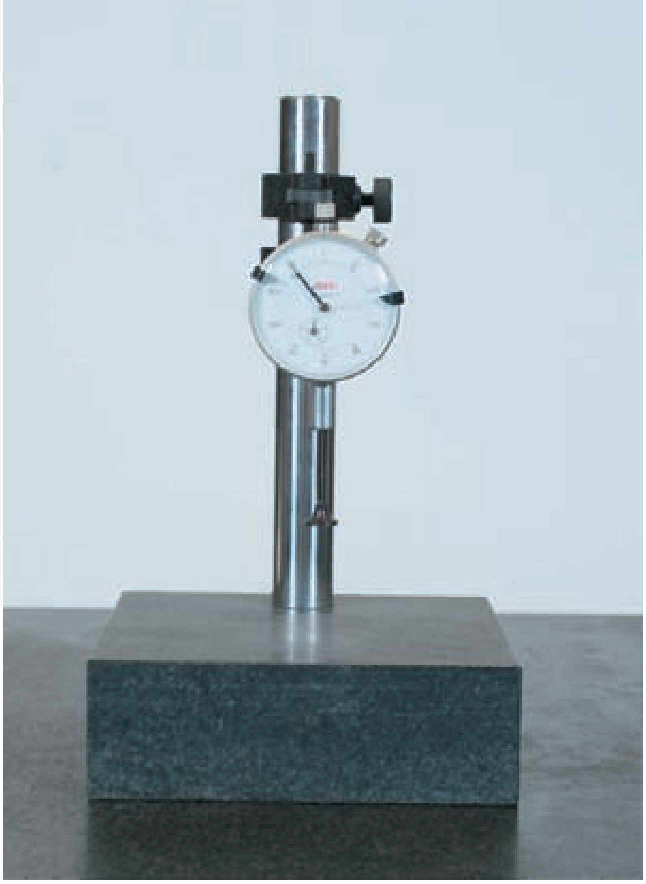


Figure C-204 Dial indicator comparator.

Figure C-205 Setting the dial indicator to zero using gage blocks.

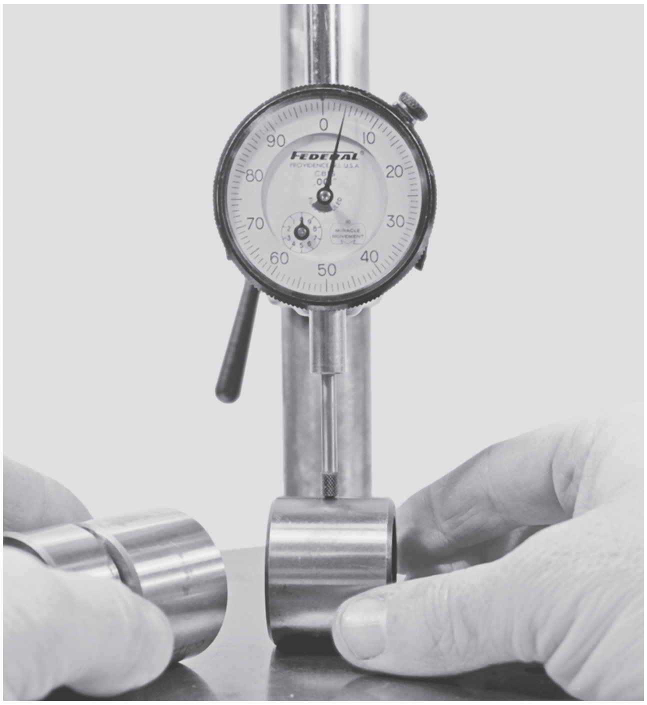


Figure C-206 Using the dial indicator comparator.

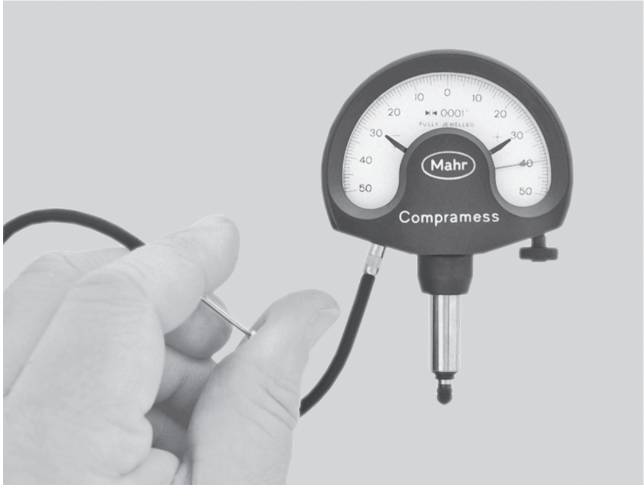


Figure C-207 Dial indicator comparator with cable lift.

Electronic Digital Indicator Comparators Microelectronic technology has been adapted to indicator comparators as well as to many other instruments. With digital readouts, these instruments are easy to read and calibrate, and they demonstrate high reliability and high discrimination. One example is the digital indicator comparator (Figure C-208).

This instrument may be coupled to a microcomputer that will print and graph measurements as they are taken. The system (Figure C-209) is highly suited to quality control inspection measurement in the machine shop.

Figure C-208 Digital electronic comparator (*Mitutoyo America Corp.*).

Figure C-209 Digital electronic comparator with computer and printer (*Mitutoyo America Corp.*).

Profile Projectors The profile projector (Figure C-210) projects onto a screen a greatly magnified profile of the object being measured. Various templates or patterns in addition to graduated scales can be placed on the screen and compared with the projected shadow of the part. The optical comparator is particularly useful for inspecting the geometry of screw threads, gears, and formed cutting tools.

Electronic and digital readouts also appear on the profile projector. These features increase this instrument's reliability, ease of operation, metric/inch selection, high discrimination, and high sensitivity (Figure C-211).

Electromechanical and Electronic Gaging Electromechanical and electronic comparators convert dimensional change into changes of electric current or voltage. These changes are read on a suitably graduated scale (meter). Economical mass production of high-precision parts requires that fast and reliable measurements be made so that over- and undersized parts can be sorted from those within tolerance. Electronic gaging can be used in this application (Figure C-212). The gaging shown is used to check a shaft.

Figure C-210 Profile projector (*Mitutoyo America Corp.*).

Figure C-211 Profile projector with built-in linear scales (*Mitutoyo America Corp.*).

Figure C-212 Electromechanical comparator inspecting a camshaft (*Courtesy Mahr Federal Inc.*).

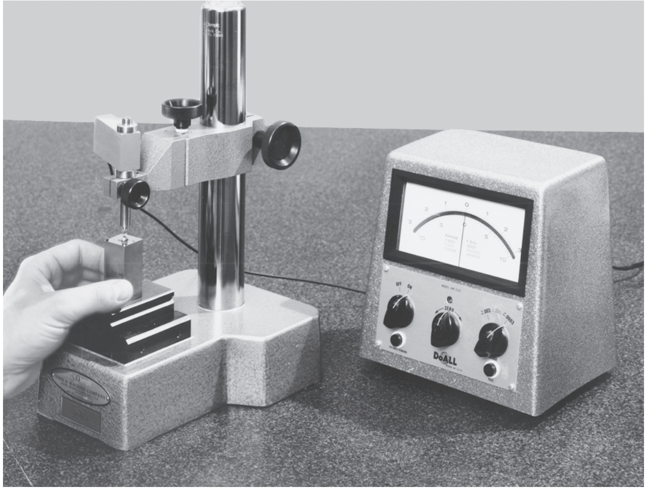


Figure C-213 Electronic comparator with maximum discrimination of .00001 in. (*Courtesy of DoALL Company*).

The electronic comparator (Figure C-213) is a sensitive instrument. It is used in a variety of comparison measuring applications in inspection and calibration. The comparator is set to a gage block by first adjusting the coarse adjustment. This mechanically moves the measuring probe. Final adjustment to zero is accomplished electronically. This is one of the unique advantages of such instruments. The electronic comparator shown has three scales. The first scale reads ±.003 in. at full range, with a discrimination of .0001 in. The second scale reads ±.001 in. at full range, with a discrimination of .00005 in. The third scale reads ±.0003 in. at full range, with a discrimination of .00001 in.

SHOP TIP

Remember that comparison measurement is exactly what the name implies, a comparison between an unknown dimension and the setting of a tool representing the unknown. The tool representing the unknown may or may not have any inherent capability to show a measurement.

There can be a loss of reliability in making this type of measurement, especially when it involves the physical transfer and comparison of one tool with another, as comparison techniques often do. Control as many variables as possible, and if necessary, repeat the measurement several times. If you can obtain the same result from several repetitions of the measurement, reliability and the likelihood that the measurement is correct will be greatly enhanced.

SELF-TEST

1. Define *comparison measurement.*
2. What can be said of most comparison measuring instruments?
3. Define *cosine error.*
4. How can cosine error be reduced?

Match the following measuring situations with the list of comparison measuring tools. Answers may be used more than once.

5. A milled slot 2 in. wide with a tolerance of ±.002 in.
6. A height transfer measurement
7. The shape of a form lathe cutter
8. Checking a combination square to determine its accuracy
9. The diameter of a $1\frac{1}{2}$- in. hole
10. Measuring a shim under a piece of machinery.

    a. Spring caliper
    b. Telescope gage
    c. Adjustable parallel
    d. Radius gage
    e. Thickness gage
    f. Planer gage
    g. Combination square
    h. Solid beam square
    i. Beveled edge square
    j. Cylindrical square
    k. Diemaker's square
    l. Micrometer square
    m. Dial indicator
    n. Dial test indicator
    o. Dial indicator comparator
    p. Optical comparator
    q. Electronic comparator

INTERNET REFERENCES

Information on comparison measuring instruments:

http://www.prattandwhitney.com
http://dialindicator.com
http://www.measurenow.com
http://www.starrett.com
http://mitutoyo.com

UNIT SIX

Using Gage Blocks

In the introduction to this section we discussed the need for standardization of measurement. Today's widespread manufacturing can function only if machinists everywhere are able to check and adjust their measuring instruments to the same standards. Gage blocks permit a comparison between the working measurement instruments of manufacturing and recognized international standards of measurement. They are one of the most important measuring tools you will encounter. The practical uses of gage blocks in the metrology laboratory, toolroom, and machine shop include the calibration of precision measuring instruments, the establishment of precise angles, and, often, measurements involved in the positioning of machine tool components and cutting tools.

OBJECTIVES

After completing this unit, you should be able to:

- Describe the care required to maintain gage block accuracy.
- Wring gage blocks together correctly.
- Disassemble gage block combinations and prepare the blocks properly for storage.
- Calculate combinations of gage block stacks with and without wear blocks.
- Describe gage block applications.

GAGE BLOCK TYPES AND GRADES

Gage blocks are commonly available individually or in sets. A common gage block set will contain 81 to 88 blocks ranging in thickness from .050 to 4.000 in. The total measuring range of the set is over 25 in. (Figure C-214). Also available are 121-block sets that permit measurement from .010 to 18 in.

Figure C-214 Gage block set with accessories (*Courtesy of DoALL Company*).

Sets with 4, 6, 9, 12, and 34 blocks are also used depending on measuring requirements. Sets of extra-long blocks are available permitting measurements to 84 in. Metric gage block sets contain blocks ranging from .5 to 100 mm. Angular gage blocks can measure from 0 to 30 degrees. Gage blocks for linear measurement are either rectangular or square.

The three grades of gage blocks are grade 1 (laboratory), grade 2 (inspection), and grade 3 (shop) (Table C-1). Grades 1 and 2 are manufactured grades. Grade 3 blocks are compromises between grades 1 and 2. Sets of grade 3 can be purchased, or they may be created by assembling out-of-tolerance grade 2 and 3 gage blocks that do not meet the tolerances for grade 1. Grade 3 blocks are not used by the inspection or gage laboratory but are acceptable in the shop for many typical measurement applications.

Table C-1 Gage Block Tolerances

	Tolerances in Microinches (.000001 in.) for Gage Block Grade		
Size	**Grade 1 (Formerly AA)**	**Grade 2 (Formerly A+)**	**Grade 3 (between A and B)**
1 in. and less	+2 −2	+4 −2	+8 −2
2 in.	+4 −4	+8 −4	+16 −8
3 in.	+5 −5	+10 −5	+20 −10
4 in.	+6 −6	+12 −6	+24 −12

THE VALUE OF GAGE BLOCKS

As you know, a truly exact size cannot be obtained. However, it can be quite closely approached. Gage blocks are one of the physical standards that can closely approach exact dimensions. This makes them useful as measuring instruments with which to check other measuring tools. From the table on gage block tolerances, you can see that the length tolerance on a grade 1 block is ±.000002 in. This is only four millionths of an inch total tolerance. Such a small amount is hard to visualize. Consider that the thickness of a page of this book is about .003 in. Compare this amount with total gage block tolerance and you will note that the page is 750 times thicker than the tolerance. This should indicate that a gage block would be useful for checking a measuring instrument with .001 or even .0001 in. discrimination.

As a further demonstration of gage block value, consider the following example. You want to establish a distance of 20 in. as accurately as possible. Using a typical gage block set, imagine a hypothetical situation in which each block has been made to the plus tolerance of .000002 in. over the actual size. This situation would not exist in an actual gage block set, as the tolerance of each block is most likely bilateral. If it required 30 blocks to make up a 20-in. stack, the cumulative tolerance would amount to .000060 in. (60 millionths). As you can see, the 20-in. length is still extremely close to actual size. In a real situation, because of the bilateral tolerance of the gage blocks, the 20-in. stack will actually be much closer to 20.000000 than to 20.000060 in. Because the gage block is so close to actual size, cumulative tolerance has little effect even over a long distance.

PREPARING GAGE BLOCKS FOR USE

Gage blocks are rugged and yet delicate. During their manufacture, they are put through many heating and cooling cycles that stabilize their dimensions. For a gage block to function, its **surface** must be **extremely smooth** and **flat**.

Gage blocks are almost always used in combination, known as the *gage block stack*. The secret of gage block use lies in the ability to place two or more blocks together in such a way that most of the air between them is displaced. This is the process of **wringing**. Once this is accomplished, atmospheric pressure will hold the stack together. The space or interface between wrung gage blocks is known as the *wringing interval*. Properly wrung gage block stacks are essential if cumulative error is to be avoided. Two gage blocks simply placed against each other will have an air layer between them. The thickness of the air layer will greatly affect the accuracy of the stack.

Before gage blocks can be wrung, they must be properly prepared. Burrs, foreign material, lint, grit, and even dust from the air can prevent proper wringing and permanently damage a gage block. The main cause of gage block wear is the wringing of poorly cleaned blocks. Preparation of gage blocks should conform to the following procedure.

Step 1 Remove the desired blocks from the box and place them on a lint-free tissue. The gage blocks should be handled as little as possible so that heat from fingers will not temporarily affect size.

Step 2 The gage block must be cleaned thoroughly before wringing. This can be done with an appropriate cleaning solvent or commercial gage block cleaner (Figure C-215). Use the solvent sparingly, especially if an aerosol is applied. The evaporation of a volatile solvent can cool the block and cause it to temporarily shrink out of tolerance.

Step 3 Dry the block immediately with a lint-free tissue.

Step 4 Any burrs on a gage block can prevent a proper wring and possibly damage the highly polished surface.

Figure C-215 Applying gage block cleaner.

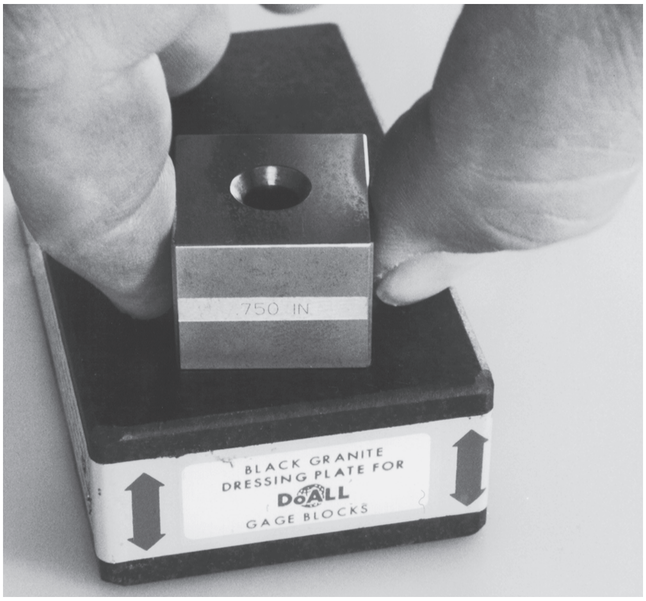


Figure C-216 Using the conditioning stone.

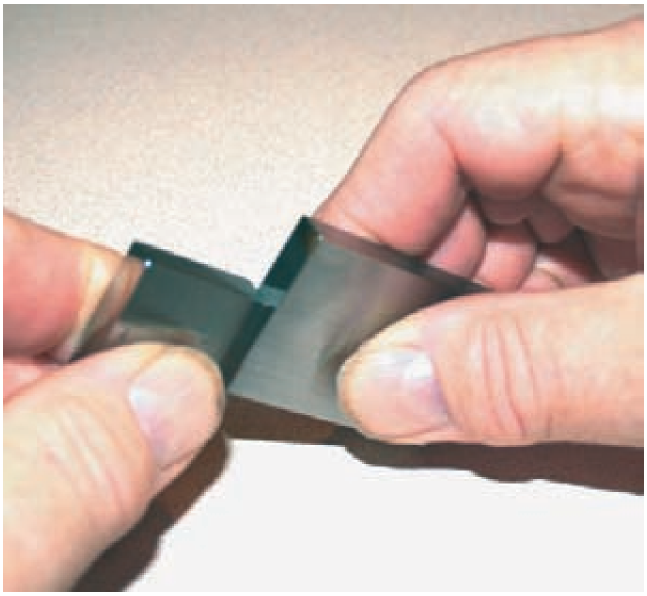


Figure C-217 Overlapping gage blocks prior to wringing.

Deburring is accomplished with a special deburring stone or dressing plate (Figure C-216). The block should be lightly moved over the stone using a single back-and-forth motion. After deburring, the block must be cleaned again.

WRINGING GAGE BLOCKS

Gage blocks should be wrung immediately after cleaning. If more than a few seconds elapse, dust from the air will settle on the wringing surface. The block may require dusting with a camel's hair brush. To wring rectangular gage blocks, the following procedure should be used.

Step 1 Place the freshly cleaned and deburred mating surfaces together and overlap them about $\frac{1}{8}$ in. (Figure C-217).

Step 2 Slide the blocks together while lightly pressing together. During the sliding process, you should feel an increasing resistance. This resistance should then level off.

Step 3 Position the blocks so that they are in line (Figure C-218).

Step 4 Make sure that the blocks are wrung by holding one block and releasing the other. Hold your hand under the stack in case the block should fall (Figure C-219).

Square gage blocks require the same cleaning and deburring as rectangular blocks. Square gage blocks are wrung by a slightly different technique. Since they are square, they should be placed together at a 45-degree angle. The upper block is then slid over the lower block while at the same time twisting the blocks and applying a light pressure.

Figure C-218 Wrung gage blocks in line.

During the wringing process, heat from the hands may cause the block stack to expand, often well out of tolerance. The stack should be placed on a heat sink to normalize the temperature. Generally, gage blocks should be handled as little as possible to minimize heat problems.

If during the wring the blocks tend to slide freely, slip them apart immediately and recheck cleaning and deburring. If the blocks fail to wring after the proper preparation procedure has been followed, they may be warped or have a surface imperfection. A gage block may be inspected for these conditions by using an optical flat.

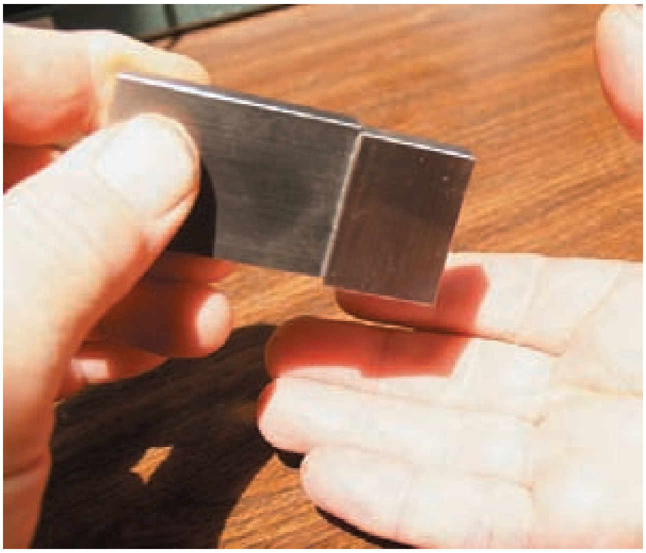


Figure C-219 Making sure of a proper wring.

Figure C-220 Round and square optical flats (*Courtesy of DoALL Company*).

CHECKING GAGE BLOCKS WITH OPTICAL FLATS

An **optical flat** is an extremely flat piece of quartz (Figure C-220). Like gage blocks, flats come in various grades. First-grade or reference optical flats are flat to within .000001 in. (one millionth). Round optical flats range from 1 to 10 in. in diameter. Square flats range from 1 × 1 in. to 4 × 4 in.

The optical flat uses the principles of **light interferometry** to make measurements and reveal surface geometry undetected by other means. The working surface of the flat is placed on the gage block (Figure C-221). The block and flat are then placed under a single-color or **monochromatic** light source. Since it is not possible to produce a truly flat surface, some surface deviation will exist even on the most perfect of gage blocks. Therefore, a portion of the block will be in direct contact with the optical flat. Other portions will not be in contact.

In the areas of no contact, a small space exists between the optical flat and the gage block. Monochromatic light passing through the optical flat is reflected by both the lower surface of the flat and the surface of the gage block. Under certain conditions, dependent on the distance existing between block and flat, light reflected from the block surface will cancel light reflected from the lower surface of the optical flat. This cancellation effect, called **interference,** is directly related to the distance between block and flat. If this distance is the same as or proportional to the wavelength of the light used, interference can occur (Figure C-222). The result of interference produces a dark band, or **interference fringe** (Figure C-223). Interference can occur only at half a wavelength or at a multiple of half a wavelength (Figure C-224). Since the wavelength of the monochromatic light is known, measurement of the spacing of the fringe patterns is used to determine the actual amount of surface deviation.

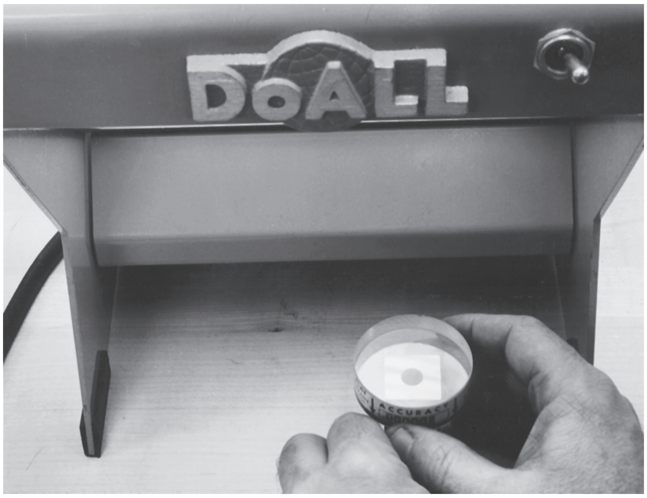


Figure C-221 Inspecting a gage block under monochromatic light.

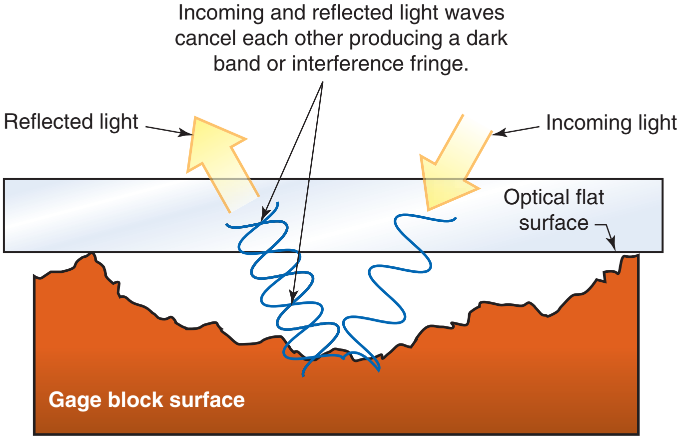


Figure C-222 The optical flat in light interference.

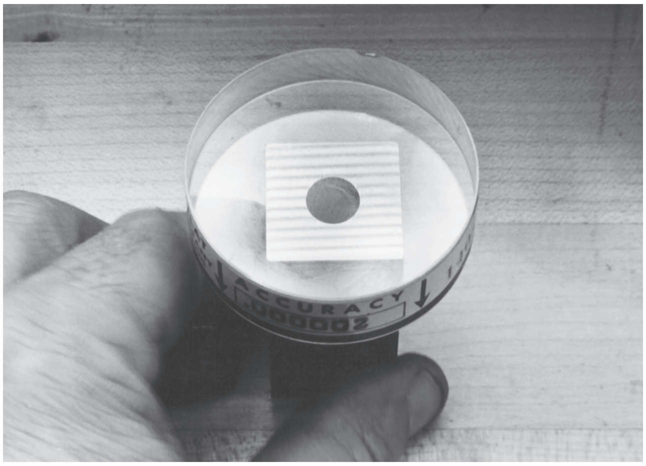


Figure C-223 Interference fringe patterns.

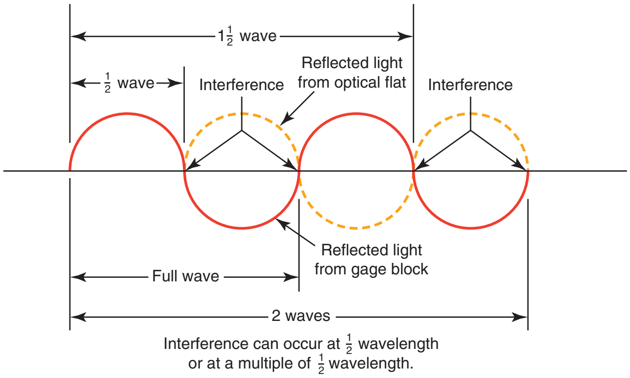


Figure C-224 Points of light interference.

Figure C-225 Handle gage blocks only with tissue.

Figure C-226 Applying gage block preservative.

PREPARING GAGE BLOCKS FOR STORAGE

Gage block stacks should not be left wrung for extended periods of time. The surface finish can be damaged in as little as a few hours' time, especially if the blocks were not exceedingly clean at the time of wringing. After use, the stack should be unwrung and the blocks cleaned once again. Blocks should be handled with tissue (Figure C-225). Each block should be sprayed with a suitable gage block preservative and replaced in the box. The entire set should then be lightly sprayed with gage block preservative (Figure C-226).

CALCULATING GAGE BLOCK COMBINATIONS

In making a gage block stack, use a minimum number of blocks. Each surface or wringing interval between blocks can increase the opportunity for error, and poor wringing can make this error relatively large. To check your wringing ability, assemble a combination of blocks totaling 4.000 in. Compare this stack with the 4.000-in. block under a sensitive comparator. Make the comparison immediately after wringing to observe the effect of heat on the stack length. Place the wrung stack on a special heat sink or on the surface plate for about 15 minutes and then check the length again. This will provide a reasonable estimate of the wringing interval. Two millionths of an inch per interval is considered good wringing.

Table C-2 gives the specifications of a typical set of 83 gage blocks. Note that they are in four series.

In the following example, it is desired to construct a gage block stack to a dimension of 3.5752 in. Wear blocks will be used on each end of the stack.

3.5762	
−.100	First, eliminate two .050-in. wear blocks.
3.4762	
−.1002	Then, eliminate the last figure right,
3.3760	by subtracting the .1002-in. block.

Table C-2 Typical 83-Piece Gage Block Set

***First:* .0001 Series—9 Blocks**										
.1001	.1002	.1003	.1004	.1005	.1006	.1007	.1008	.1009		
***Second:* .001 Series—49 Blocks**										
.101	.102	.103	.104	.105	.106	.107	.108	.109		
.110	.111	.112	.113	.114	.115	.116	.117	.118		
.119	.120	.121	.122	.123	.124	.125	.126	.127		
.128	.129	.130	.131	.132	.133	.134	.135	.136		
.137	.138	.139	.140	.141	.142	.143	.144	.145		
.146	.147	.148	.149							
***Third:* .050 Series—19 Blocks**										
.050	.100	.150	.200	.250	.300	.350	.400	.450	.500	.550
.600	.650	.700	.750	.800	.850	.900	.950			
***Fourth:* 1.000 Series—4 Blocks**										
			1.000	2.000	3.000	4.000				
				2	.050 wear blocks					

.126 3.250	Once again, eliminate the last figure right, by subtracting the .126-in. block.
−.250 3.000	Eliminate the last figure right, using the .250-in. block.
−3.000 0.000	Eliminate the 3.000 in. with the 3.000-in. block.

Therefore, the blocks required to construct this stack are

Quantity	Size
2	.050-in. wear blocks
1	.1002-in. block
1	.126-in. block
1	.250-in. block
1	3.000-in. block

As a second example, we shall construct a gage block stack of 4.2125 without wear blocks.

$$\begin{array}{r} 4.2125 \\ \underline{-.1005} \\ 4.1120 \\ \underline{-.112} \\ 4.0000 \\ \underline{-4.0000} \\ 0.0000 \end{array}$$

Blocks for this stack are

Quantity	Size
1	.1005
1	.112
1	4.000

USING WEAR BLOCKS

When gage blocks are used in applications that include direct contact, it is advisable to use **wear blocks.** For example, if you were using a gage block stack to calibrate a large number of micrometers, wear blocks would reduce the wear on the gage block. Wear blocks are usually included in typical gage blocks sets. They are made from the particularly hard material tungsten carbide. A wear block is placed on one or both ends of a gage block stack to protect it from possible damage by direct contact. Wear blocks are usually .050 or .100 in. thick.

GAGE BLOCK APPLICATIONS

Gage blocks are used in setting sine bars for establishing precise angles. The use of the sine bar is discussed in the unit on angular measure. Gage blocks are used to set other measuring instruments such as a snap gage (Figure C-227). The proper blocks are selected for the desired dimension and the stack is assembled (Figure C-228). Since this is a direct contact application, wear blocks should be used. The stack is then used to set the gage (Figure C-229).

Gage block measurement is facilitated by various accessories (Figure C-230). Accessories include scribers, bases, gage pins, and screw sets for holding the stack together. In any application where screws are employed to secure gage block stacks, a torque screwdriver must be used. This will apply the correct amount of pressure on the gage block stack. Gage blocks and accessories can be assembled into precision height gages for layout (Figure C-231). With gage pins (Figure C-232), gage blocks may

Figure C-227 Gage and wear blocks for setting a snap gage.

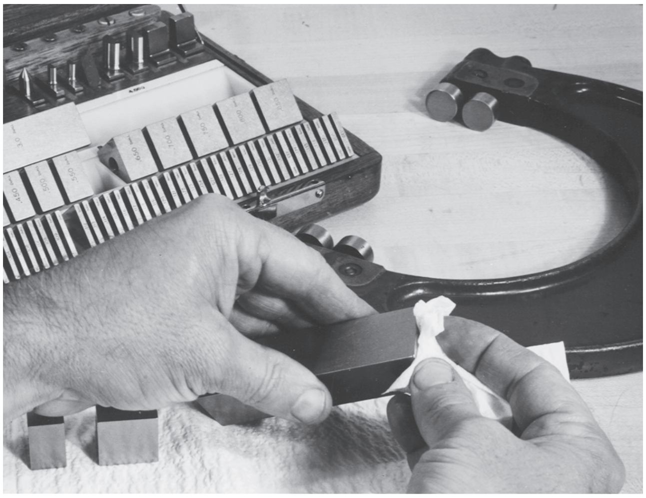


Figure C-228 Cleaning blocks prior to wringing.

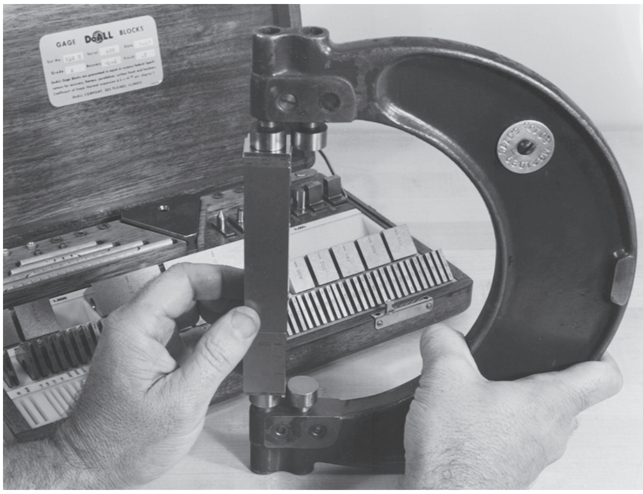


Figure C-229 Setting a snap gage using gage blocks.

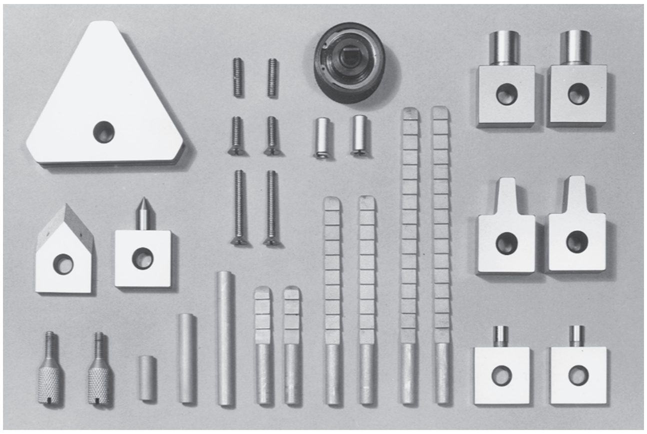


Figure C-230 Gage block accessories.

be used for direct gaging or for checking other measuring instruments. Machine tool applications include the use of gage blocks as auxiliary measuring systems on milling machines, for setting cutter heights, and for spacing straddle milling cutters.

SHOP TIP

Gage blocks are invaluable tools in the machine shop as well as the toolroom and calibration lab. Always handle them with care and use proper procedures for cleaning, wringing, and storing. The gage block can add a high degree of reliability and accuracy to many machine shop measurements, machine and inspection setups, and calibration procedures.

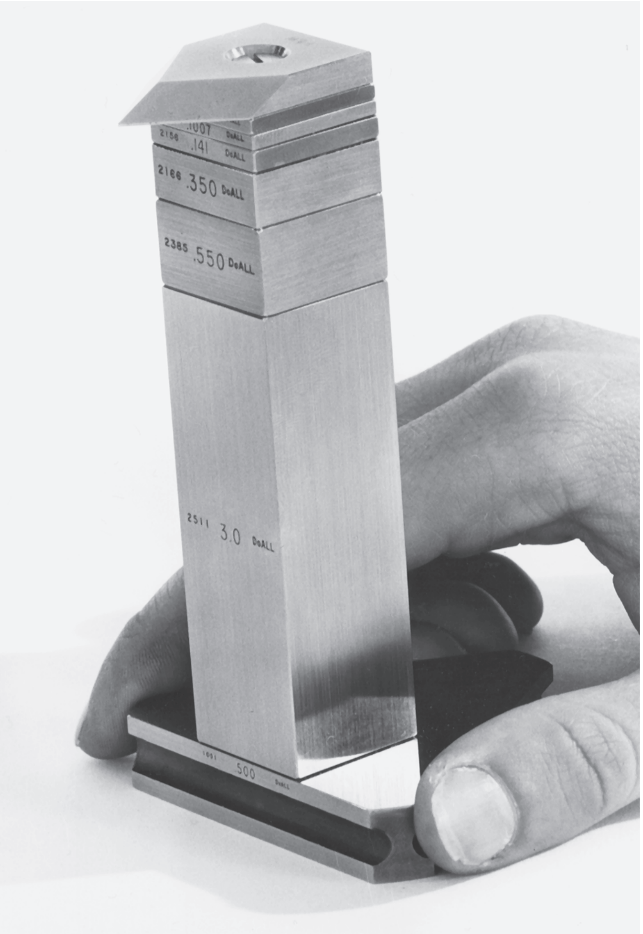


Figure C-231 Precision height gage assembled from gage blocks (*Courtesy of DoALL Company*).

Figure C-232 Gage block stack with accessory gage pins (*Courtesy of DoALL Company*).

SELF-TEST

1. What is a *wringing interval*?
2. Why are wear blocks frequently used in combination with gage blocks?
3. As related to gage block use, what is meant by the term *normalize*?
4. What length tolerances are allowed for the following grades of gage blocks (under 2.000-in. sizes): grade 1; grade 2; grade 3?
5. What is a conditioning stone and how is it used?
6. What does the term *microinch* regarding surface finish of a gage block mean?
7. Describe the handling precautions necessary for the preservation of gage block accuracy.
8. What gage blocks are necessary to assemble a stack equal to 3.0213 without using wear blocks?
9. List gage blocks necessary for a stack equal to 1.9643 with wear blocks.
10. Describe at least two gage block applications.

INTERNET REFERENCES

Information on gage blocks:

http://starrett.com

http://mitutuyo.com

http://www.fvfowler.com

UNIT SEVEN

Using Angular Measuring Instruments

Angular measurement is as important as linear measurement. The same principles of metrology apply to angular measure as to linear measure. Angular measuring instruments have various degrees of discrimination. They must not be used beyond their discrimination. Angular measuring instruments require the same care and handling as any other of your precision tools.

OBJECTIVES

After completing this unit, you should be able to:

- Identify common angular measuring tools.
- Read and record angular measurements using a vernier protractor.
- Calculate sine bar elevations and measure angles using a sine bar and adjustable parallels.
- Calculate sine bar elevations and establish angles using a sine bar and gage blocks.

TYPES OF ANGLES

As a machinist, you will need to measure **acute angles**, **right angles**, and **obtuse angles** (Figure C-233). Acute angles are less than 90 degrees. Obtuse angles are more than 90 degrees but less than 180 degrees. Ninety-degree or right angles are generally measured with squares. However, the amount of angular deviation from perpendicularity may have to be determined. This requires that an angular measuring instrument be used. Straight angles, or those of 180 degrees, generally fall into the category of straightness or flatness and are measured by other types of instruments.

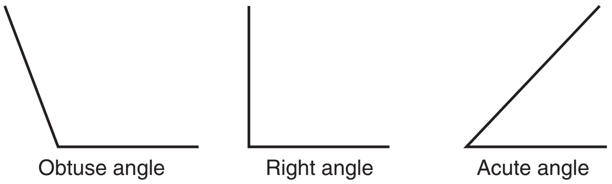


Figure C-233 Acute, right, and obtuse angles.

UNITS OF ANGULAR MEASURE

In the inch system, the unit of angular measure is the **degree**.

$$\begin{aligned} \text{Full circle} &= 360 \text{ degrees} \\ 1 \text{ degree} &= 60 \text{ minutes of arc } (1^\circ = 60') \\ 1 \text{ minute} &= 60 \text{ seconds of arc } (1' = 60'') \end{aligned}$$

In the metric system, the unit of angular measure is the **radian**. A radian is the angle at the center of a circle that is subtended by an arc on the circumference that is equal in length to the radius of the circle (Figure C-234). Since the circumference of a circle is equal to $2\pi r$ (radius), there are 2π radians in a circle. Converting one radian to degrees gives the equivalent:

$$1 \text{ radian} = \frac{360}{2\pi r}$$

Assuming a radius of 1 unit:

$$\begin{aligned} 1 \text{ radian} &= \frac{360}{2\pi} \\ &= 57^\circ 17' 44'' \text{ (approximately)} \end{aligned}$$

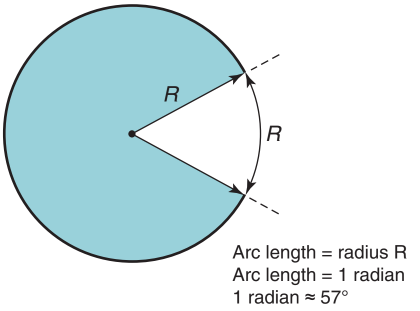


Figure C-234 Radian measure.

It is unlikely that you will come in contact with much radian measure. All the common comparison measuring tools you will use read in degrees and fractions of degrees. Metric angles expressed in radian measure can be converted to degrees by the equivalent shown.

REVIEWING ANGLE ARITHMETIC

You may find it necessary to perform angle arithmetic. Use your calculator, if you have one available.

Adding Angles

Angles are added just like any other quantity. One degree contains 60 minutes. One minute contains 60 seconds. Any minute total of 60 or larger must be converted to degrees. Any second total of 60 or larger must be converted to minutes.

EXAMPLES

$$35^\circ + 27^\circ = 62^\circ$$
$$3^\circ 15' + 7^\circ 49' = 10^\circ 64'$$

Since $64' = 1^\circ 4'$, the final result is $11^\circ 4'$.

$$265^\circ 15' 52'' + 10^\circ 55' 17'' = 275^\circ 70' 69''$$

Since $69'' = 1'9''$ and $70' = 1^\circ 10'$, the final result is $276^\circ 11' 9''$.

Subtracting Angles

When subtracting angles where borrowing is necessary, degrees must be converted to minutes and minutes must be converted to seconds.

EXAMPLES

$$15^\circ - 8^\circ = 7^\circ$$
$$15^\circ 3' - 6^\circ 8' \text{ becomes}$$
$$14^\circ 63' - 6^\circ 8' = 8^\circ 55'$$
$$39^\circ 18' 13'' - 17^\circ 27' 52'' \text{ becomes}$$
$$38^\circ 77' 73'' - 17^\circ 27' 52'' = 21^\circ 50' 21''$$

Decimal Angles

When using digital readout measuring and dividing equipment for angular measurement, you may encounter angle fractions in decimal form rather than minutes and seconds. For example, 30 degrees 30 minutes would be $30\frac{1}{2}$ degrees or 30.5 degrees. You should familiarize yourself with angle decimal fractions and the methods of converting minutes and seconds to their decimal equivalents.

Decimal fractions of angles are calculated by the following procedures. Since there are 60 minutes in each degree, a fractional portion of a degree becomes a fraction of 60.

EXAMPLES

32 minutes is $\frac{32}{60}$ of 1 degree. Converting to a decimal fraction:

$$\frac{32}{60} = .5333 \text{ degrees}$$

23 seconds is $\frac{23}{60}$ of 1 minute:

$$\frac{23}{60} = .3833 \text{ minute}$$

To convert angle decimal fractions to minutes and seconds, multiply the decimal portion times 60.

EXAMPLES

45.5 degrees converted to minutes: The decimal portion is $.5 \times 60 = 30$ minutes, or 45.5 degrees = 45 degrees and 30 minutes

32.75 degrees converted to minutes: The decimal portion is .75 degree $\times\ 60 = 45$ minutes, or 32 degrees and 45 minutes

Some calculators can convert decimal fractions of angles to minutes and seconds. Other calculators require these computations to perform conversions.

ANGULAR MEASURING INSTRUMENTS

Plate Protractors

Plate protractors have a discrimination of one degree and are useful in such applications as layout and checking the point angle of a drill (Figure C-235).

Bevel Protractors

The bevel protractor is part of the machinist's combination set. This protractor can be moved along the rule and locked in any position. The protractor has a flat base, permitting it to rest squarely on the workpiece (Figure C-236). The combination set protractor has a discrimination of one degree.

Dial-Indicating Sinometer Angle Gage

The indicating sinometer (Figure C-237) permits fast and accurate measurement of all angles. Discrimination is 30 seconds of arc per dial division.

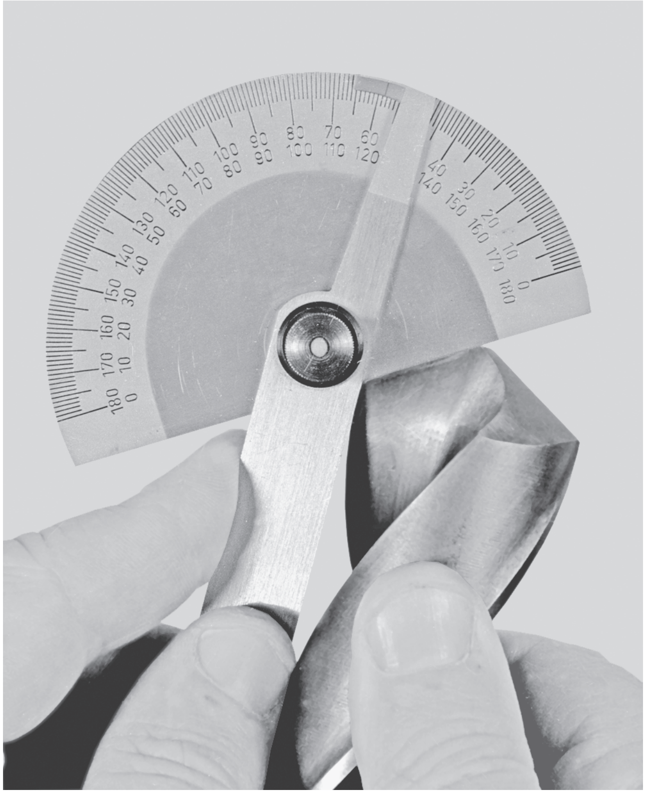


Figure C-235 Plate protractor measuring a drill point angle.

Figure C-236 Using the combination set bevel protractor.

Universal Bevel Vernier Protractor

The universal bevel vernier protractor (Figure C-238) is equipped with a vernier that permits discrimination of $\frac{1}{12}$ of a degree, or 5 minutes of arc. The instrument can measure an obtuse angle (Figure C-239). The acute attachment facilitates the measurement of angles less than 90 degrees (Figure C-240). When used in conjunction with a vernier height gage, the universal bevel vernier protractor allows angle measurements to be made that would be difficult by other means (Figure C-241).

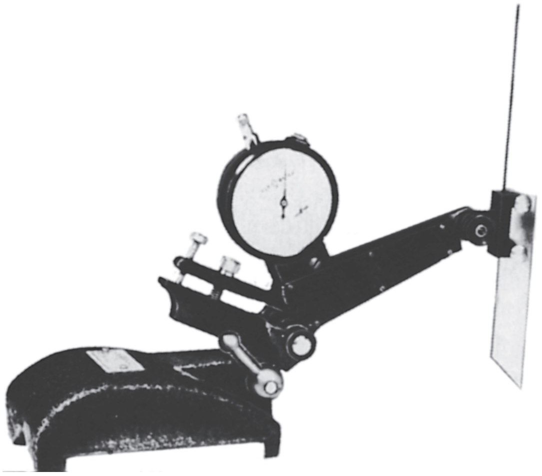


Figure C-237 Dial-indicating sinometer angle gage (*Rank Scherr-Tumico, Inc.*).

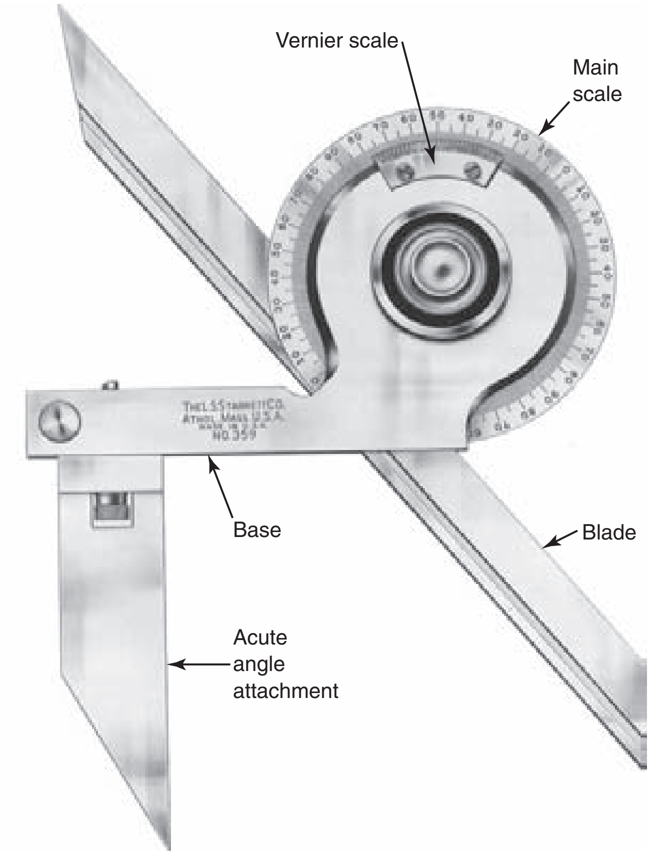


Figure C-238 Parts of the universal bevel vernier protractor (*Courtesy of The L.S. Starrett Co.*).

Vernier protractors are read like any other instrument employing the vernier. The main scale is divided into whole degrees. These are marked in four quarters of 0 to 90 degrees each. The vernier divides each degree into 12 parts, each equal to 5 minutes of arc.

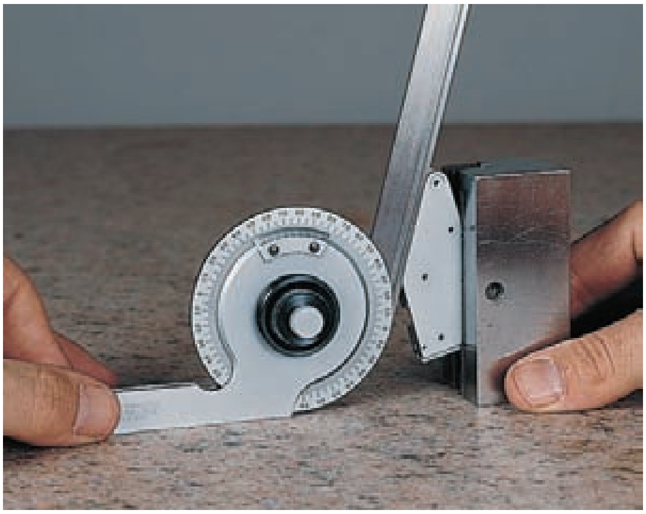


Figure C-239 Measuring an obtuse angle with the vernier protractor (*Courtesy of The L.S. Starrett Co.*).

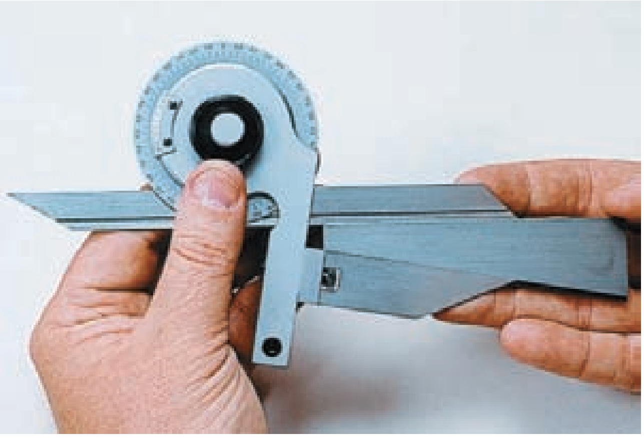


Figure C-240 Using the acute angle attachment (*Courtesy of The L.S. Starrett Co.*).

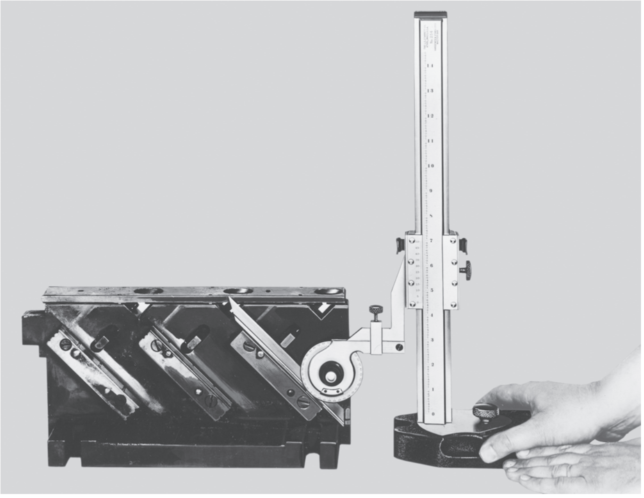


Figure C-241 Using the vernier protractor in conjunction with the vernier height gage (*Courtesy of The L.S. Starrett Co.*).

To read the protractor, determine the nearest full degree mark between zero on the main scale and zero on the vernier scale. **Always read the vernier in the same direction as you read the main scale.** Determine the number of the vernier coincident line. Since each vernier line is equal to 5 minutes, multiply the number of the coincident line by 5. Add this value to the main scale reading.

EXAMPLE READING

The protractor shown in Figure C-242 has a magnifier so that the vernier may be seen more easily.

Main scale reading: 56°
Vernier coincident at line 6
6 × 5 minutes = 30 minutes
Total reading: 56°30′

For convenience, the vernier scale is marked at 0, 30, and 60, indicating minutes.

The vernier bevel protractor can be applied in a variety of angular measuring applications (Figure C-243).

RIGHT-TRIANGLE TRIGONOMETRY: THE SINE RATIO

Trigonometry, the branch of mathematics that deals with triangle measurement, has many applications in machine shop work. A working knowledge of right-triangle trigonometry is essential to being a competent machinist, and you should begin to learn the basics of this math as early as possible in your training.

Right-triangle trigonometry deals with the relationships or ratios of the lengths of the sides of a right triangle. In Figure C-244, right triangle *ABC* is shown in the standard notation, where the angles are identified by uppercase letters (*A*, *B*, *C*) and the sides of the triangle are identified

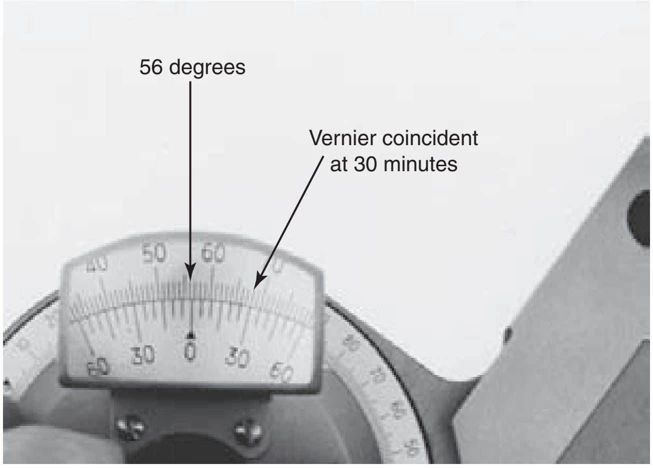


Figure C-242 Vernier protractor reading of 56 degrees and 30 minutes.

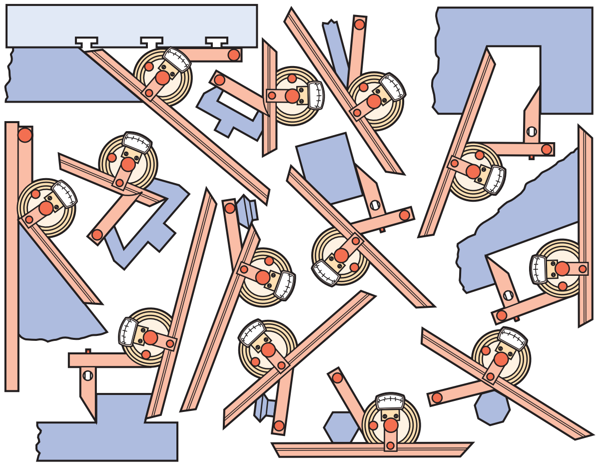


Figure C-243 Applications of the vernier bevel protractor (*Mitutoyo America Corp.*).

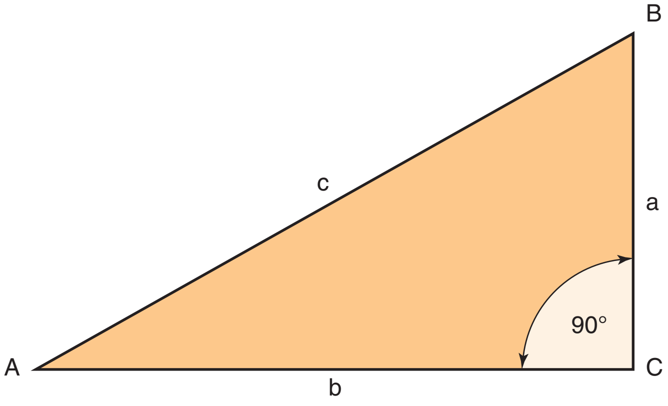


Figure C-244 Standard notation for a right triangle.

by lowercase letters (*a, b, c*). In standard triangle notation, the side opposite an angle carries the same letter as the angle. Therefore, side *a* is opposite angle *A*. Side *b* is opposite angle *B,* and side *c,* the long side, is opposite angle *C,* which is the right or 90-degree angle.

The two **acute** angles, *A* and *B*, are so called because they are always less than 90 degrees. Angle *C* is always a right or 90-degree angle formed by the two short legs *a* and *b.* Side *c* is the longest side of the triangle and is called the **hypotenuse**. When you add the three angles in the right triangle, the sum is always 180 degrees. Since angle *C* is 90 degrees, the sum of angles *A* and *B* is therefore 90 degrees (Figure C-245). This is the first piece of basic information that you need to know about right triangles.

$$\angle A + \angle B = 90^\circ$$

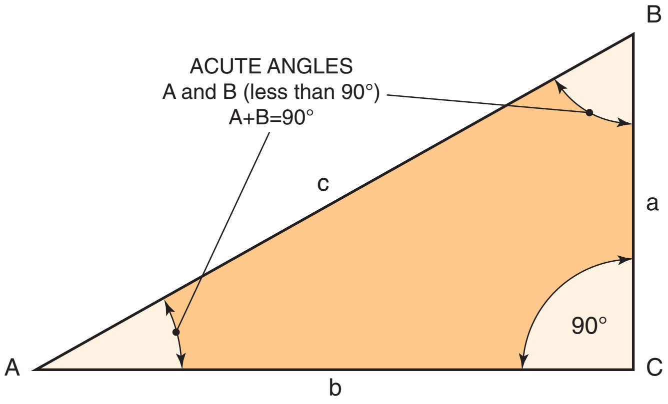


Figure C-245 Acute angles of a right triangle.

The angles of the triangle are dimensioned and measured in degrees of arc. Arc units (degrees) are not the same kind of units as linear units of measure, such as inches or feet. In *Unit 6* you learned about various tools that can measure angles in arc units of measure. However, in the machine shop it is often both necessary and better to measure angles not in terms of degrees of arc but as functions of linear units such as inches and fractions. The reason for this is that most machine tools, particularly milling machines, have major components that move only at right angles to each other. There is no capability to position these machine components in terms of arc units of measurement (degrees). Therefore, arc measurements of angles or angular displacement of features on a workpiece must be expressed as functions of linear measurement units such as inches and fractions. These techniques are often used when programming bolt circle patterns and machining angles in CNC work.

The use of the **sine bar** is a classical example of a tool used to establish and measure angles as functions of linear units. The sine bar makes use of the **sine ratio** in right-triangle trigonometry. The **sine (sin)** of an angle is defined as the ratio of the length of the side opposite an acute angle to the length of the hypotenuse, or

$$\sin = \frac{\text{side opposite}}{\text{hypotenuse}}$$

For example, the sine of angle *A* is defined as

$$\text{sin of angle } A \text{ or } \sin A = \frac{\text{side opposite}}{\text{hypotenuse}} = \frac{a}{c}$$

The size of the acute angles *A* and *B* in the right triangle control the length of the triangle's sides. Similarly, the length of the sides *a* and *b* control the sizes of the acute angles (Figure C-246). Therefore, the size of angles and the length of sides may be expressed in terms of each other. This is to say that for a given specified length of sides, as measured in linear units, the acute angles must be a corresponding size, as measured in degrees of arc.

Consider the following specific case. In the triangle shown in Figure C-247, the ratio of side *a* to side *c,* the hypotenuse, is .5 to 1. In other words, the side opposite angle *A,* side *a,* is exactly half as long as side *c.* For this to be true, angle *A* must then be exactly 30 degrees, which then makes

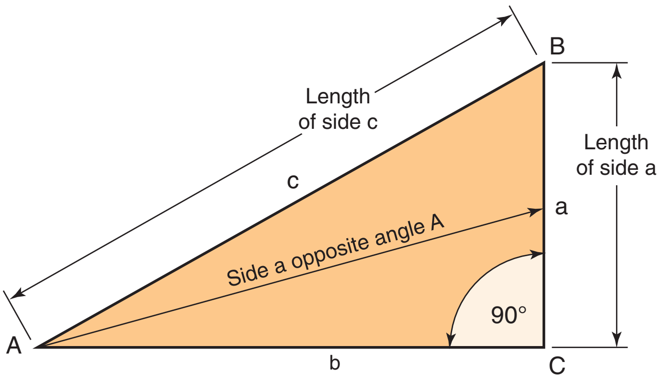


Figure C-246 The ratio of the length of side *a* to side *c* defines the sin of angle *A*.

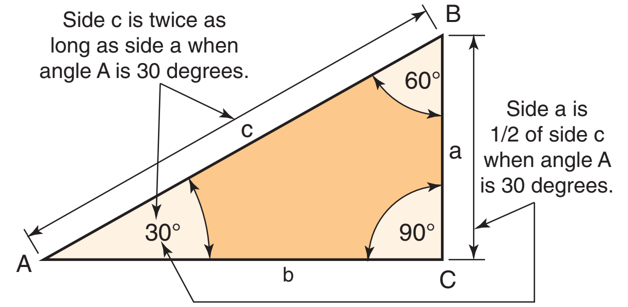


Figure C-247 30-60-90 right triangle.

angle *B* equal to 60 degrees. If the ratio of *a* to *c* were not .5 to 1, the size of angles *A* and *B* would have to be different as well. The ratio of *a* to *c* (*a/c*) defines the **sine of angle *A*.** When *a* is divided by *c,* the result is .5/1 = .5. You may then use a trig function table or a calculator to determine what angle corresponds to a sine value of .5. Look in the trig function table under the sine column and locate the .5000 entry. You will see that the corresponding angle is 30 degrees. On a calculator .5 is entered and the inverse (or second function) sin key is pressed. The displayed result is 30 degrees.

In this specific case, where angle *A* and angle *B* are 30 and 60 degrees, respectively, the length of side *c,* the hypotenuse, is always twice that of side *a,* no matter what the actual length is of sides *a* and *c*. Another way to state this relationship is simply to say that **the side opposite a 30-degree angle is always half the length of the hypotenuse.** This information is useful for a machinist when dealing with the 30-60-90 right triangle, which finds many applications in machine shop work. In later units, methods to calculate the length of side *b* will be developed.

Using the Sine Bar

The sine bar (Figure C-248) is a typical example of a tool used to both measure and establish precise angles by inferring their size in degrees as a function of linear units of measure. The sine bar consists of a hardened and precision-ground steel bar with a cylinder attached to each end. The distance between the centerlines of the cylinders is precisely established at either 5 or 10 inches. This is done to make the sine bar calculations more convenient. The sine bar is placed on the surface plate and becomes the hypotenuse of a right triangle. The angle to be measured or established is the acute angle between the surface plate and the sine bar's top surface. This becomes angle *A* in the standard triangle. By elevating the other end of the sine bar a specific amount, you control the ratio between the side opposite the acute angle formed between the surface plate and the sine bar's top surface. Since this defines the sine ratio (opposite side/hypotenuse), the amount of bar elevation varies the length of the opposite side and also varies the acute angle between surface and sine bar.

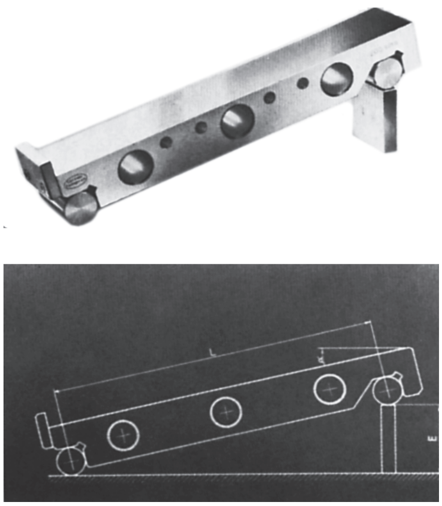


Figure C-248 Sine bar (*Mahr Gage Company*).

Because the length of the sine bar is a fixed dimension, either 5 or 10 in., it is easy to determine the angle from trig table entries or from a calculator. Since the sine is defined by the equation

$$\sin A = \frac{\text{side opposite}}{\text{hypotenuse}}$$

transposing the equation gives

$$\text{side opposite} = (\text{hypotenuse}) \times (\text{sine of the angle desired})$$

On the sine bar, this becomes

$$\text{bar elevation (the side opposite angle } A\text{)} = [\text{bar length (the hypotenuse)}] \times (\text{sine of the angle desired})$$

Since standard sine bars are either 5 or 10 in. long, the bar-length multiplier in the preceding equation is simply 5 or 10 times the sine of the angle. If you are establishing an angle with the side bar, use the equation

$$\text{bar elevation} = (\text{bar length}) \times (\text{sine of the angle desired})$$

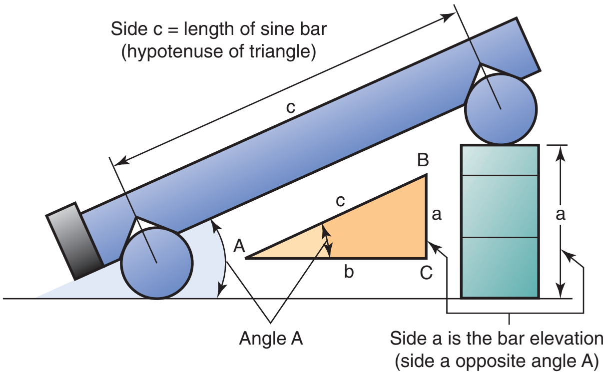


Figure C-249 Elevating the sine bar with gage blocks.

If you are determining an angle on a workpiece, adjust the bar elevation until the reference edge of the workpiece is set parallel to the surface plate (Figure C-249). Then, measure the height of the elevation and use this value to determine the sine of the angle established:

$$\text{sine of angle desired} = \frac{\text{elevation}}{\text{length of sine bar}}$$

$$\text{size of angle (in degrees)} = \text{arc sine or inverse sine}$$

EXAMPLE

Determine the elevation for 30 degrees using a 5-in. sine bar.

$$\begin{aligned}\text{bar elevation} &= 5\text{ in.} \times \text{sine } 30^\circ\\ &= 5 \times .5\\ &= 2.500\text{ in.}\end{aligned}$$

This means that if the bar was elevated 2.500 in., an angle of 30 degrees would be established.

EXAMPLE

Determine the elevation for 42 degrees using a 5-in. sine bar.

$$\begin{aligned}\text{bar elevation} &= 5\text{ in.} \times \text{sine } 42^\circ\\ &= 5 \times .6691\\ &= 3.3456\text{ in.}\end{aligned}$$

Determining Workpiece Angle Using the Sine Bar and Measuring Workpiece Angle Using the Sine Bar and Adjustable Parallel

An angle may be measured using the sine bar and adjustable parallel. The adjustable parallel is used to elevate the sine bar (Figure C-250). The workpiece is placed on the sine bar, and a dial test indicator is set to zero on one end of the part (Figure C-251). The parallel is adjusted until the dial indicator reads zero at each end of the workpiece (Figure C-252). The parallel is then removed and measured with a micrometer (Figure C-253). To determine the angle of the workpiece,

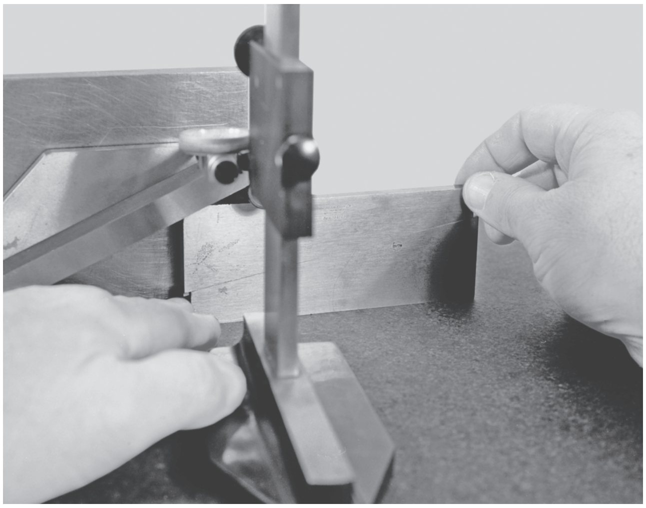


Figure C-250 Placing the adjustable parallel under the sine bar.

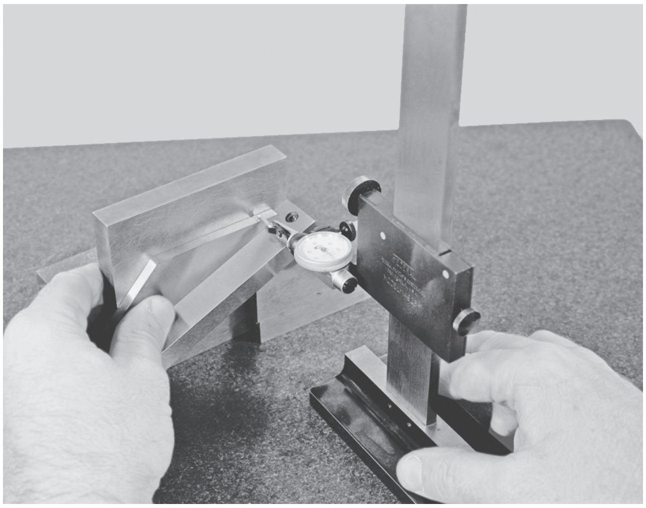


Figure C-251 Setting the test indicator to zero at the end of the workpiece.

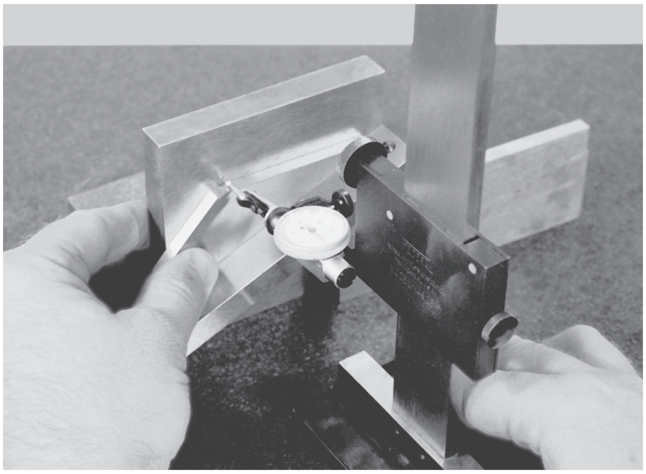


Figure C-252 Checking the zero reading at the opposite end of the workpiece.

Figure C-253 Measuring the adjustable parallel with an outside micrometer.

simply transpose the sine bar elevation formula and solve for the angle.

bar elevation = bar length × sine of the angle desired

sine of the angle desired = elevation/bar length

sine of angle = 1.9935 (micrometer reading/5)

sine = .3987

angle = 23°29′48″

Establishing Angles Using the Sine Bar and Gage Blocks

Extremely precise angles can be measured or established by using gage blocks to elevate the sine bar. Bar elevation is calculated in the same manner. The required gage blocks are properly prepared, and the stack is wrung (Figure C-254). The gage block stack totaling 1.9940 in. is placed under the bar (Figure C-255). This will establish an angle of 23°30′11″ using a 5-in. sine bar. The angle of the workpiece is checked using a dial test indicator (Figure C-256).

Sine Bar Constant Tables

The elevations for angles up to about 55 degrees can be obtained directly from a **table of sine bar constants**. Such tables can be found in the Appendix of this text and in

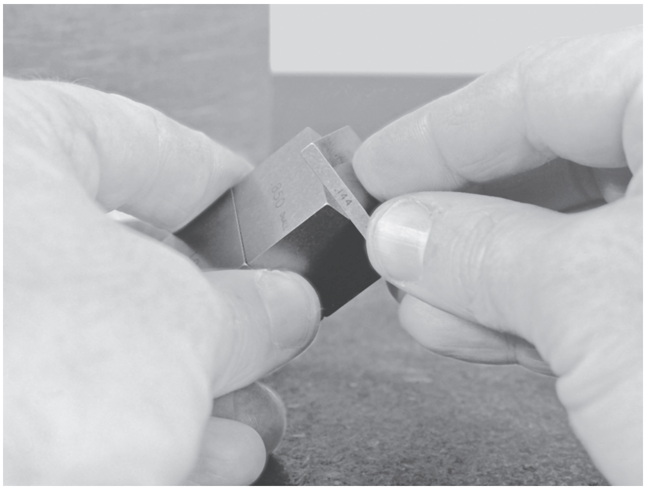


Figure C-254 Wringing the gage block stack for the sine bar elevation.

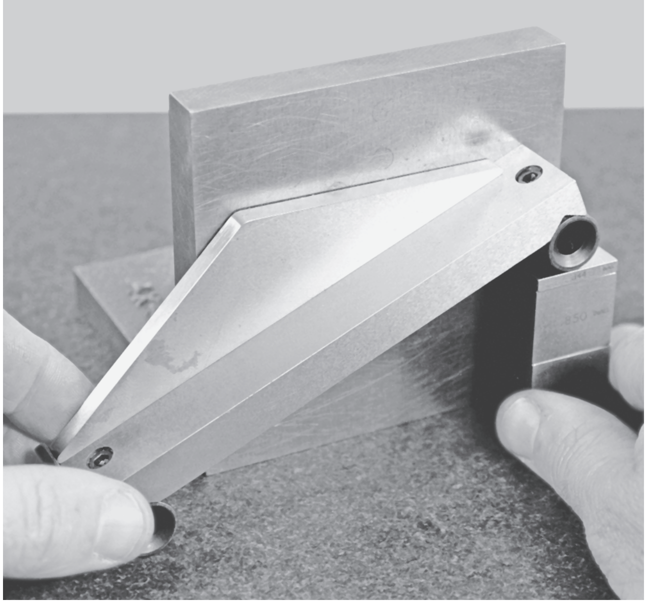


Figure C-255 Placing the gage block stack under the sine bar.

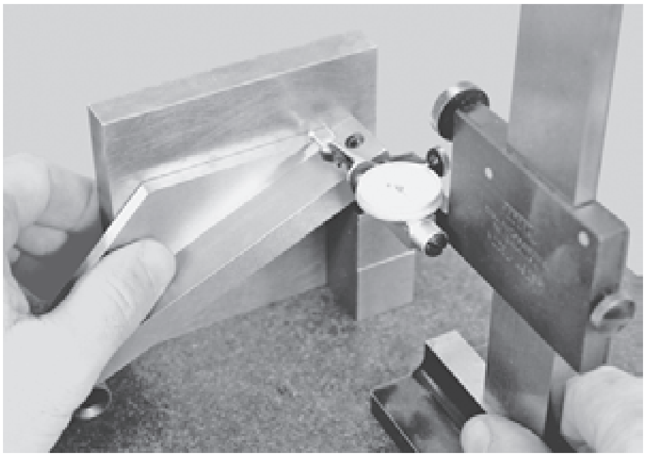


Figure C-256 Checking the workpiece using the dial test indicator.

machinists' handbooks. The sine bar constant table eliminates the need to perform a trigonometric calculation. The sine bar table may discriminate only to minutes of arc. If discrimination to seconds of arc is required, it is better to calculate the amount of sine bar elevation required.

SELF-TEST

1. Name two angular measuring instruments with one degree of discrimination.
2. What is the discrimination of the universal bevel protractor?
3. Describe the use of the sine bar.
4. Read and record the vernier protractor readings in Figures C-257*a* to C-257*e*.
5. Calculate the required sine bar elevation for an angle of 37 degrees. (Assume a 5-in. sine bar.)
6. A 10-in. sine bar is elevated 2.750 in. Calculate the angle established to the nearest minute.
7. How do 10-in. and 5-in. sine bars affect the height of gage block stacks?
8. What gage block stack would establish an angle of 35 degrees using the 5-in. sine bar?
9. What gage block stack would establish an angle of 23.5 degrees using the 5-in. sine bar?
10. A 10-in. bar is elevated 2.5 in. What angle is established?

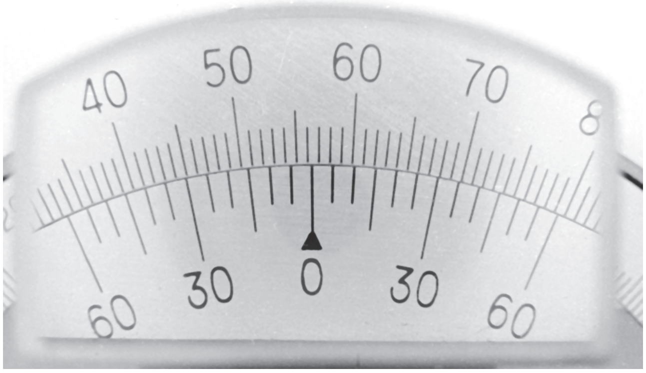


Figure C-257*a*

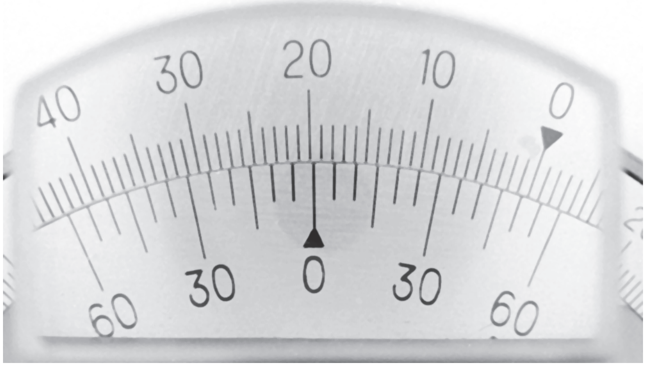


Figure C-257*b*

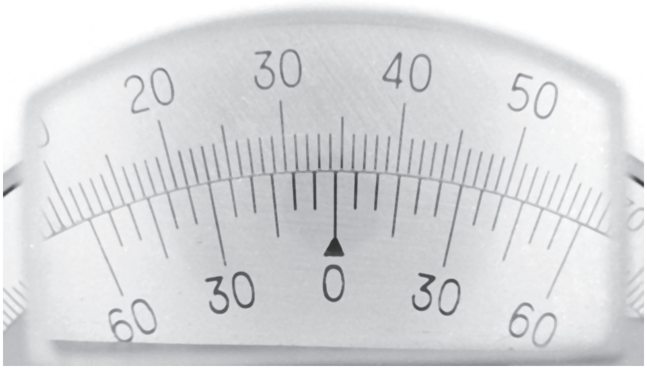


Figure C-257*c*

Figure C-257*d*

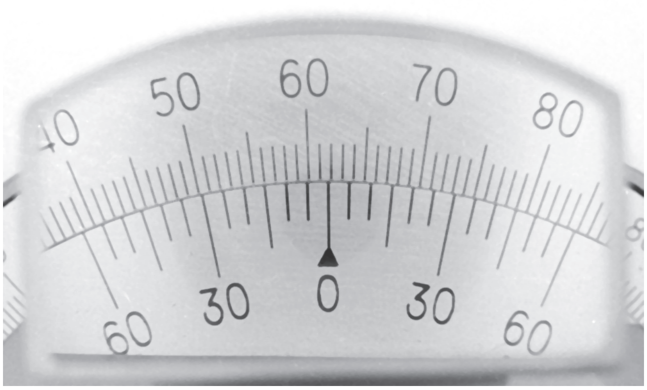


Figure C-257*e*

INTERNET REFERENCES

Information on angular measurement tools:

http://fvfowler.com

http://mitutuyo.com

http://starrett.com

http://www.gemred.com

UNIT EIGHT

Tolerances, Fits, Geometric Dimensions, and Statistical Process Control (SPC)

Almost no product today is totally manufactured by a single maker. Although you might think that a complex product like an automobile or aircraft is made by a single manufacturer, if you looked behind the scenes you would discover that the manufacturer uses many suppliers that make components for the final assembly.

To make all the component parts fit together, or **interface**, to form a complex assembly, you have already learned that a standardized system of measurement is essential. You have further learned that the measurement instruments must be compared with known standards in the process of **calibration** in order to maintain their accuracy.

Although standardized measurement is essential to modern industry, perhaps even more important are the design specifications that indicate the **dimensions** of a part. These dimensions control the sizes of a part, its features, and/or their locations on the part or relative to other parts. Consequently, parts can be interchanged and mated to one another to form complete assemblies.

Although the size of part features is important, dimensions that pertain to part geometry may be equally important. For example, a part with a specific pattern of holes may require that the location of the holes be as exact as the size of the holes themselves. In this case, the geometric dimensions and tolerances pertaining to the true position of part features apply and must be met in the machining process as well as in the inspection of the final product.

The methods and tools of statistical process control (SPC) are used to track the dimensions of machined parts, especially those produced by computer-controlled machining processes (CNC). SPC can determine whether the machining process is producing in-tolerance parts and can measure and record many other factors about the parts including tolerance, average size, deviation from nominal dimensions, and distributions of part dimensions about the nominal dimensional specifications. SPC is useful in determining the exact point where a manufacturing process is failing to meet specifications.

This unit introduces the basic terminology and concepts of tolerances, fits, geometric dimensions, and statistical process control.

OBJECTIVES

After completing this unit, you should be able to:

- Describe the basic reasons for tolerance specifications.
- Recognize common geometric dimensions and tolerances.
- Describe the reasons for press fits and know where to find press fit allowance information.
- Describe the general terms and purpose of SPC.

LIMIT AND TOLERANCE

Since it is impossible to machine a part to an exact size, a designer must specify an acceptable range of sizes that will still permit the part to fit and function as intended. The maximum and minimum sizes in part dimensions are **limits** between which the actual part dimension must fall. The difference between the maximum and minimum limits is **tolerance**, or the total amount by which a part dimension may vary. Tolerances on drawings are often indicated by specifying a limit, or by **plus** and **minus** notations (Figure C-258).

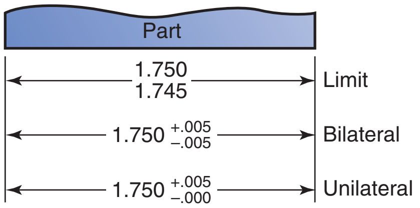


Figure C-258 Tolerance notations.

With plus-minus tolerancing, when the tolerance is both above and below the nominal (true theoretical) size, it is said to be **bilateral** (two-sided). When the tolerance is indicated all on one side of nominal, it is said to be **unilateral** (one-sided).

TOLERANCE EXPRESSION: DECIMAL INCH

Unilateral Tolerance: .750 + .005 .750 + .000
− .000 − .005

The zero tolerance must have the same number of decimal places as the numeric tolerance and must include a plus or a minus sign.

Bilateral Tolerance: .750 ± .005 *not* .75 ± .005

When bilateral tolerancing is used, both the size and the plus-minus tolerance must have the same number of decimal places.

Limit Dimensioning

When limit dimensioning is used, both upper and lower limits must have the same number of decimal places.

.500 *instead of* .5
.495 .495

TOLERANCE EXPRESSION: METRIC

Millimeters

Unilateral Tolerance: 24.0 *or* 24 + 0.03
− 0.03 − 0

A single zero is shown without a plus or minus sign.

Bilateral Tolerancing: 23 − 0.03 24 + 0.03
− 0.05 + 0.05

Both the plus and minus tolerances must have the same number of decimal places.

Limit Dimensioning: 24.00 *or* 24.03
23.97 24.00

Both the upper and lower limits must have the same number of decimal places.

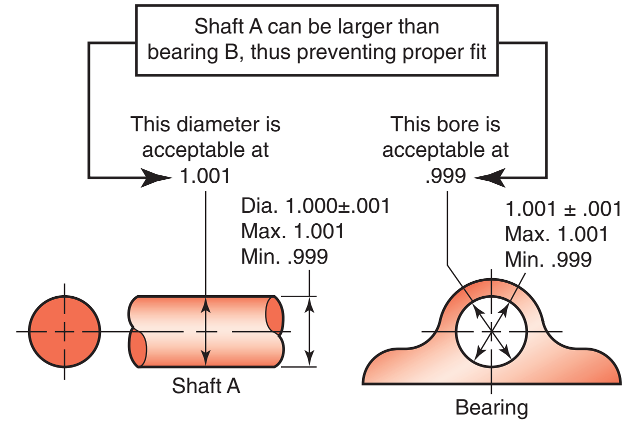


Figure C-259 Tolerance overlap can prevent proper fit of mating parts.

HOW TOLERANCE AFFECTS MATING PARTS

When two parts mate or are interchanged in an assembly, tolerance becomes vitally important. Consider the following example (Figure C-259): the shaft must fit the bearing and be able to turn freely. The diameter of the shaft is specified as 1.000 ± .001. This means that the maximum limit of the shaft is 1.001 and the minimum is .999. The tolerance is then .002 and bilateral.

The maximum limit of the bearing bore is also 1.001 and the minimum limit is .999. The tolerance is once again .002. Will the shaft made by one machine shop fit the bearing made by another machine shop using the tolerances specified? If the shaft is turned to the maximum limit of 1.001 and the bearing is bored to its minimum limit of .999, both parts will be within acceptable tolerance but will not fit to each other, since the shaft is .002 larger than the bearing. However, if the bearing bore was specified in limit form or unilateral tolerance of 1.002 + .002 − .000, the parts would fit as intended. Even if the shaft was turned to the high limit of 1.001, it would still fit the bearing even though the bore was machined to the low limit of 1.002. Although a machinist is not usually concerned with establishing tolerance and limit specifications, you can easily see how fit problems can be created by overlapping tolerances, as discussed in this example.

STANDARD TOLERANCES

On many drawings you will use in the machine shop, tolerances will be specified at the dimensions. If no particular tolerances are specified at the dimension, accepted standard tolerances may be applied. These are often listed in part of the title block on the drawing and generally conform to the following:

Fractional dimensions ±$\frac{1}{64}$
Two-place decimal fractions ±.010
Three-place decimal fractions ±.005

Four-place decimal fractions ±.0005
Angles $\pm\frac{1}{2}$ degree

Always check any drawing carefully to determine if standard tolerances apply and what they might be for the particular job you are doing.

FITS

Fit refers to the amount or lack of clearance between two mating parts. Fits can range from free running or sliding, where a certain amount of clearance exists between mating parts, to **press** or **interference fits**, where parts are forced together under pressure. Clearance fits can range from a few millionths of an inch, such as would be the case in the component parts of a ball or roller bearing, to a clearance of several thousandths of an inch, for a low-speed drive or control lever application.

Often, a machinist is concerned with press or interference fits. In this case two parts are forced together, usually by mechanical or hydraulic pressing. The frictional forces involved then hold the parts together without any additional hardware such as keys or setscrews. Tolerances for press fits can become critical because parts can easily be damaged by attempts to press fit them if there is an excessive difference in their mating dimensions. In addition, press fitting physically deforms the parts to some extent. This can result in damage, mechanical binding, or the need for a secondary resizing operation such as hand reaming or honing after the parts are pressed together.

A typical example of press fit is the pressing of a ball bearing inner race onto a shaft, or an outer race into a bore. Thus, the bearing is retained by friction, and the free-running feature is obtained within the bearing itself. Ball-to-race clearance is only a few millionths of an inch in precision bearings. If a bearing is pressed into a bore or onto a shaft with excessive force because pressing allowances are incorrect, the bearing may be physically deformed to the extent that mechanical binding occurs. This will often cause excess friction and heat during operation, resulting in rapid failure of the part. On the other hand, insufficient frictional retention of the part resulting from a poor press fit can cause the wrong part to turn under load or some of the mechanism to fall apart while operating.

Press Fit Allowances

Press fit allowances depend on factors that include length of engagements, diameter, material, particular components being pressed, and need for later disassembly of parts. Soft materials such as aluminum can be pressed successfully. However, soft materials may experience considerable deformation, and these parts may not stand up to repeated pressings. Like metal parts pressed without the benefits of lubrication may gall, making them difficult if not impossible to press apart. Thin parts such as thin-walled tubing may bend or deform to such a degree that the press retention fails to hold the parts together under design loads. The following general rule can be applied when determining the press allowance for cylindrical parts:

$$\text{allowance} = .0015 \times \text{diameter of part in inches}$$

EXAMPLES

Determine the press allowance for a pin with a .250-in. diameter.

$$.0015 \times .250 = .000375$$
$$\text{(slightly more than } \tfrac{3}{10{,}000}\text{ in.)}$$

Determine the press allowance for a 4.250-in. diameter.

$$.0015 \times 4.250 = .00637$$
$$\text{(slightly more than } \tfrac{6}{1000}\text{ in.)}$$

Generally, pressing tolerances range from a few tenths to a few thousandths of an inch depending on the diameter of the parts and the other factors previously discussed. Proper measurement tools and techniques must be employed to make accurate determinations of the dimensions involved. For further specific dimensions on pressing allowances, consult a machinist handbook.

Press Fits and Surface Finishes

The surface finish (texture) of parts being press fitted can also play an important part. Smooth-finished parts will press fit more readily than rough-finished parts. If the roughness height of the surface texture is large (64μin. and higher), more frictional forces will be generated in the pressing operation, and the chances for misalignment, galling, and seizing will be increased, especially if no lubricant is used. Lubrication will improve this situation. However, lubrication can be detrimental to press fit retention in some cases. A few molecules of lubricant between fit surfaces, especially if they are quite smooth, can cause the parts to slip apart when subjected to certain pull or push forces.

Shrink and Expansion Fits

Parts can be fitted by making use of the natural tendency of metals to expand or contract when heated and cooled. Heating a part will expand it, and it can then be slipped on a mating part. On cooling, the heated part will contract and grip the mating part, often with tremendous force. Parts may also be mated by cooling one or the other so that it contracts, thus making it smaller. On warming to ambient temperature, it will expand to meet the mating part.

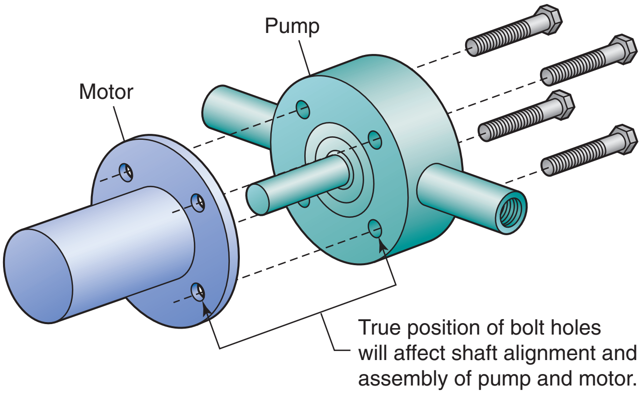
Shrink and expansion fits can have superior holding power over press fits, although special heating and cooling equipment may be necessary. As with press fits, however, allowances are extremely important. Consult a machinist handbook for proper allowance specifications.

GEOMETRIC DIMENSIONING AND TOLERANCING

Equally important—and in many cases more important than controlling the size of a particular individual part—is controlling the **form**, **orientation**, **location**, **profile**, and **runout** of a part or assembly feature. These features relate directly to the ability to interchange individualized parts and assemblies. For example, you have undoubtedly purchased standard replacement parts for your auto from many different sources. In many cases, these may be made by manufacturers other than the original maker of your auto. However, they fit and function exactly as the original equipment. To make this kind of interface possible, the manufacturing and engineering community has developed a system of geometric dimensioning and tolerancing that helps a manufacturer control form, orientation, location, profile, and runout of parts and assemblies. This system of **geometric dimensioning** and **tolerancing**—standardized in the American Society of Mechanical Engineers publication *ASME Y14.5M-1994*—is a complex subject and would require a great deal of time and space to cover completely. You will learn more about this as you go further into your training. For the present, the following discussion is intended to cover the basic concepts only.

Controlling Feature Location

You can see that to bolt the pump to the motor shown in Figure C-260, it obviously is necessary to ensure that the pattern of bolt holes in the pump matches the pattern of bolt holes in the motor. Also, the bore in the pump housing must match the boss on the motor so that the shaft will engage the motor with proper alignment. If the respective assemblies are made by different manufacturers, you can see that if either bolt pattern position deviates far from the specified dimensions, the assemblies will be difficult or impossible to interface. As long as the two manufacturers work closely together, the assemblies will interface. However, if the pump manufacturer wants to start using a motor made by another manufacturer, the bolt hole pattern on the new pump motor will also have to interface with the pattern on the pump. This is an example of a situation in which the **location** or the **true position** of the holes could be more critical than the size of the holes themselves. On drawings the following symbols are used to indicate location control:



True position of bolt holes will affect shaft alignment and assembly of pump and motor.

Figure C-260 Pump and motor bolt hole patterns must match in position to accomplish assembly.

⌖ True position
◎ Concentricity
⌯ Symmetry

Controlling Orientation

Controlling **orientation** is equally important. Consider the pump and motor assembly in the previous example. The pump drive shaft must be perpendicular to the impeller case so that it can engage the motor without mechanical binding. Therefore, **perpendicularity** is one example of form that must be controlled during manufacturing. Table C-3 shows symbols used on drawings to indicate geometric controls.

Datums and Basic Dimensions

Datums are reference points, lines, areas, and planes taken to be exact for the purpose of calculations and measurements. An initially machined surface on a casting, for example, may be selected as a datum surface and used as a

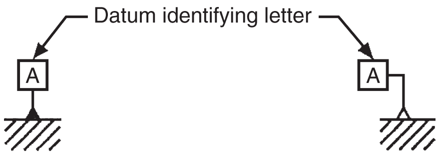
Table C-3 Geometric Characteristic Symbols

	Type of Tolerance	Characteristic	Symbol
For individual features	Form	Straightness	—
		Flatness	▱
		Circularity (roundness)	○
		Cylindricity	⌭
For individual or related features	Profile	Profile of a line	⌒
		Profile of a surface	⌓
For related features	Orientation	Angularity	∠
		Perpendicularity	⊥
		Parallelism	//
	Location	Position	⌖
		Concentricity	◎
		Symmetry	⌯
	Runout	Circular runout	↗[a]
		Total runout	⌰[a]

[a] Arrowheads may or may not be filled.

Adapted from *ASME Y14.5M-1994,* Fig. 3-1, p. 42. New York: ASME International.

reference from which to measure and locate other part features. Datums are usually not changed by subsequent machining operations and are identified by single or sometimes double letters (except I, O, and Q) inside a rectangular frame. For example,



The term **basic dimension** represents a true theoretically exact dimension describing the location or shape of a part feature. Basic dimensions have no tolerance. The tolerance comes from the associated geometric tolerances used with the basic dimension. Basic dimensions are shown on drawings by enclosing a number in a rectangle:

$\boxed{1.375}$

MMC, LMC, AND RFS

Three **material condition modifier symbols** that you will encounter on working drawings are

MMC or Ⓜ for **maximum material condition**
LMC or Ⓛ for **least material condition**
RFS or Ⓢ for **regardless of feature size**

These identify at which size the geometric tolerances apply.

MMC refers to the maximum amount of material remaining on a feature or size. On an external cylindrical feature this would be the **high limit** of the feature tolerance. For example, a shaft with a diameter of .750 ± .010 would have an MMC diameter of .760, since this would leave maximum material remaining on the part. An internal cylindrical feature such as a hole with a diameter of .750 ± .010 would have an MMC diameter of .740, since this would leave maximum material remaining on the part.

LMC works in just the opposite way. The LMC of the shaft would be .740 diameter, and the LMC of the hole would be .760 diameter. These sizes would have the least amount of material remaining on the part.

RFS, or regardless of feature size, means that the geometric tolerance applies no matter what the feature size is. The tolerance zone size remains the same, unlike MMC or LMC, which allow a tolerance zone size growth as the feature size changes.

RFS is the default condition for all geometric tolerances. Unless MMC or LMC is specified on the drawing by Ⓜ or Ⓛ, the tolerance zone size remains the same though the feature size changes. An example of RFS would be a hole located with a true position tolerance callout, where the size of the hole itself is not as important as the hole location.

Drawing Formats

The formats shown in Figure C-261 are used to express some of the common geometric dimensions and tolerances on working drawings. Geometric dimensions and tolerance symbols appear on drawings in boxes such as those shown in the figure. The first box entry is the specific geometric callout. This will be either a form or position symbol. The next box entry will indicate any datum—a point, line, or plane—from which the geometric dimension is to be measured. The third box entry specifies the tolerance zone that applies to the form or position called out by the symbol.

SHOP TIP

For further information about geometric dimensions and tolerances, consult the current edition of publication *ASME Y14.5M-1994* (reaffirmed 1999).

STATISTICAL PROCESS CONTROL (SPC)

The major objective of any manufacturing is to ensure that the end product meets design specifications. This is of the utmost importance when manufacturing the many discrete pieces that will ultimately become part of a subassembly or a complex finished product. In the modern world, many different manufacturers using a wide variety of processes are involved in producing parts for complex precision products such as automobile and aircraft engines, instruments of all types, and both the electronic and precision mechanical components of computers, to cite just a few examples.

The need to perfect manufacturing processes to a degree that will maximize good products is well known. Manufacturing at any level is expensive, so it is vital to maximize the number of product units that meet design specifications. Furthermore, there must be ways to quickly determine problems within a process so that these may be solved quickly to minimize the production of scrap or otherwise unsuitable parts. The tools and techniques of statistical process control (SPC) are effectively applied for this purpose.

Statistics may be used in at least two fundamental ways in manufacturing process control. First, this special branch of mathematics allows the manipulation of manufactured part inspection data in such ways that inferences can be made about large numbers of product units simply by selecting a representative sampling of the units, inspecting these for design specifications, and then manipulating the inspection data mathematically to make an inference about the suitability or lack thereof of the larger batch. This method saves time, as it is not necessary or even possible to inspect every part from a given production run.

Second, data obtained from inspecting product units can quickly reveal how consistent the manufacturing process is and can also reveal a point in the process where specifications are not being met. There are always imperfections in

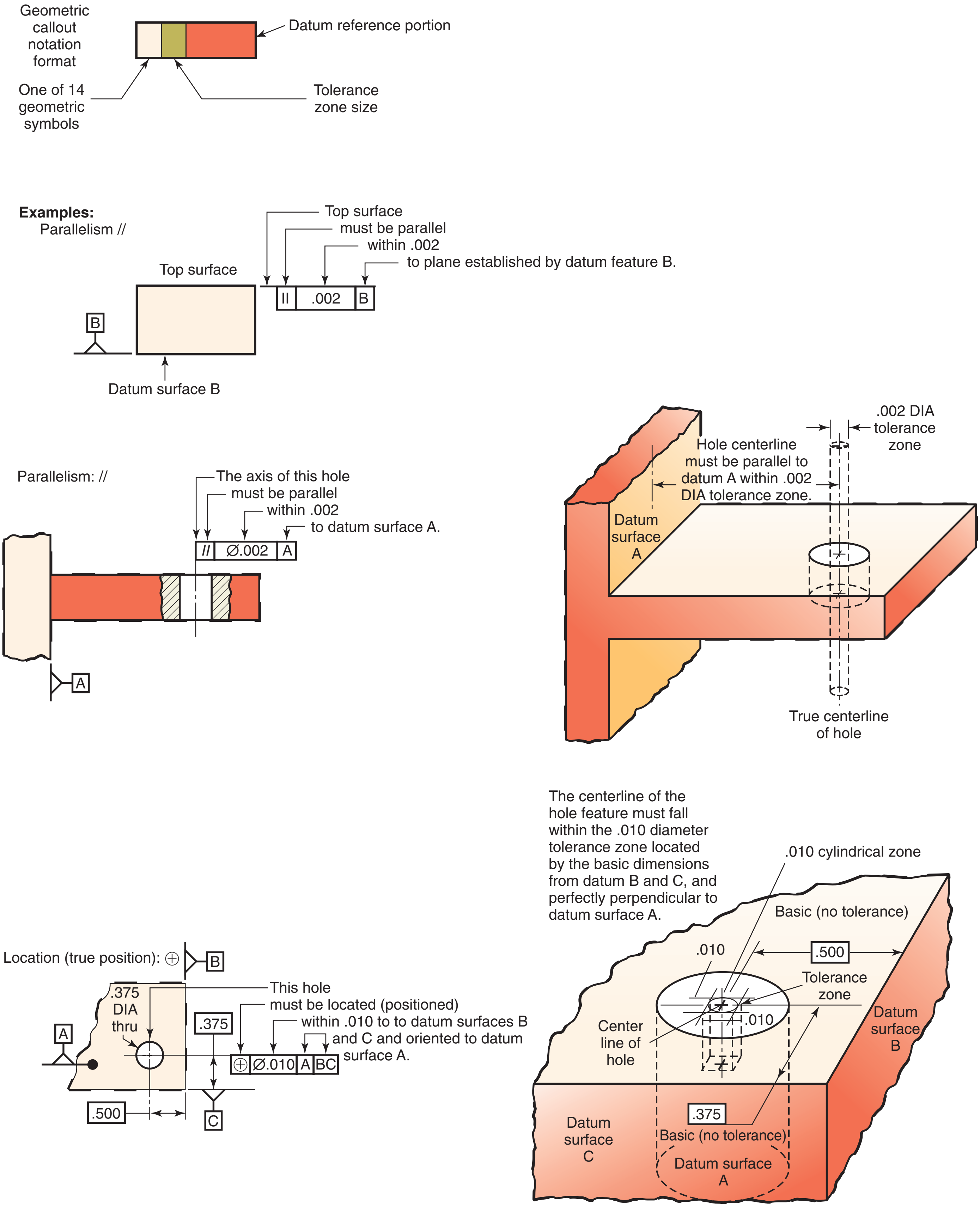


Figure C-261 Drawing formats for geometric dimension and tolerances.

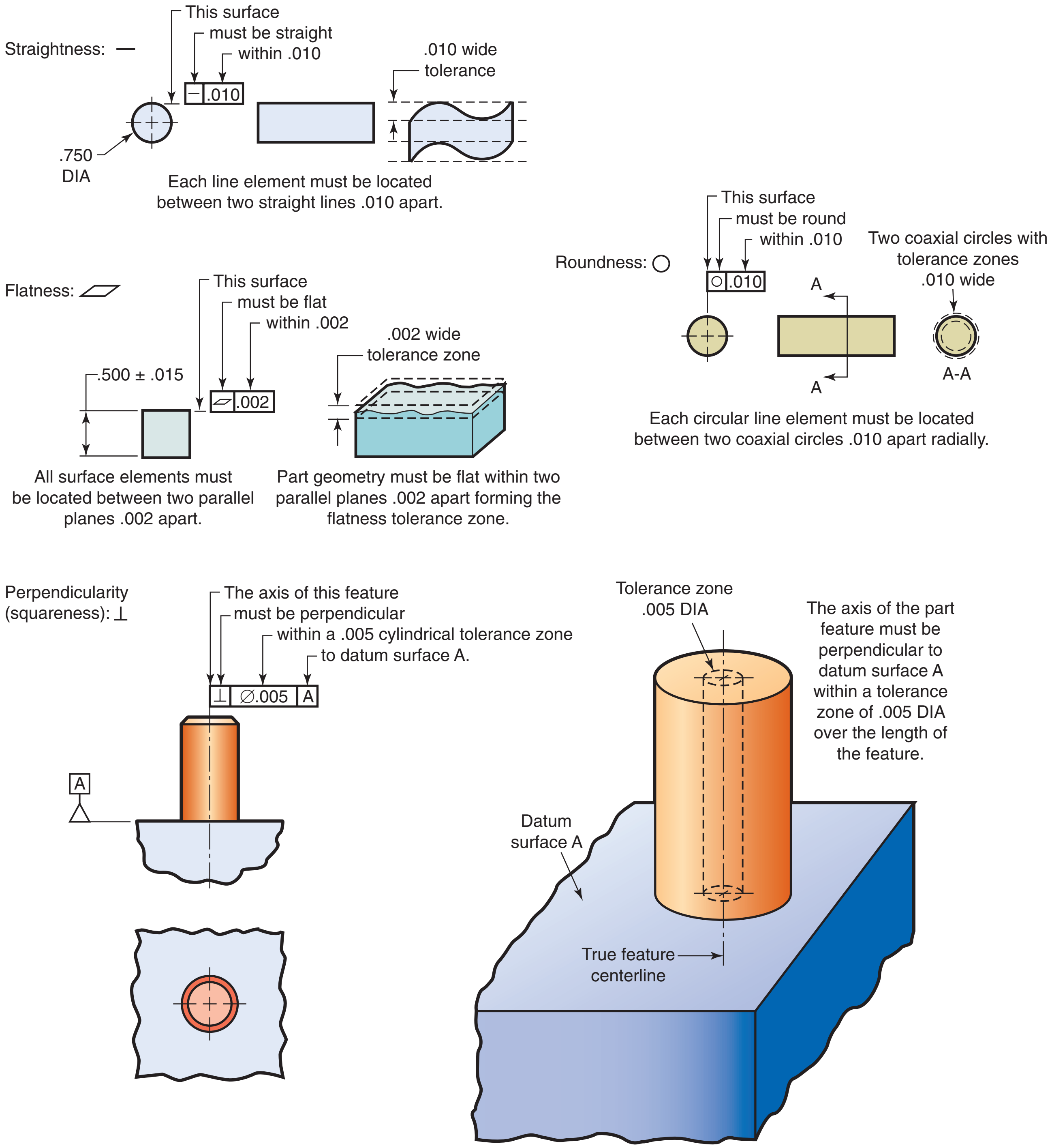


Figure C-261 (*continued*)

even the best of manufacturing equipment and processes. Machines and cutting tools wear out, operators and programmers may not be as attentive as they should, and many other factors may influence the outcome of a manufacturing process. A knowledge of information about specification discrepancies can greatly speed both the locating and the correcting of the problem. Having statistical data available allows the manufacturer to quickly determine where an adjustment or correction needs to be made in the process.

For parts made by the various machining processes, such as turning, milling, or grinding, dimensional specifications are the primary item of interest, since it is the size of the part features and often their geometry that control how well they will fit and perform with other parts. However, it should be noted that part dimensions and geometry are not the only specifications that need to be monitored during a manufacturing process. For example, the particular shade of paint, surface texture, or metallurgical specifications on a product may be equally as important as its dimensional specifications.

Various statistics are used in SPC to make determinations about product units. These statistics include arithmetic average, mean, mode, standard deviation, and correlations. Statistics may be used to measure central tendencies, average size distribution around a nominal dimension, and deviation of specifications from acceptable tolerance ranges.

A basic example of this is the arithmetic average. For example, you just measured 10 parts produced on a CNC turning center. Their nominal diameter is specified at .500 ± .010. You are interested in the average size of the 10 parts. Part dimensions are recorded as follows:

Part 1	.495	Part 6	.497
Part 2	.502	Part 7	.503
Part 3	.496	Part 8	.499
Part 4	.504	Part 9	.493
Part 5	.501	Part 10	.492

To calculate the average size of these parts and generate a statistic called the **arithmetic average,** which is one measure of central tendency, apply the following formula:

$$\frac{\text{sum of part sizes}}{\text{number of parts}} = \text{arithmetic average}$$

$$.495 + .502 + .496 + .504 + .501 + .497$$
$$+ .503 + .499 + .493 + .492 = 4.982$$

$$\frac{4.982}{10\text{ parts}} = \text{an average size of } .4982$$

In another situation you might want to know how these parts are distributed around the theoretical exact size of .500. A type of graph called a *histogram* (Figure C-262) may be developed for this purpose. The histogram is particularly useful because seeing how the dimensions of the product units are distributed can quickly show those outside the specified tolerance. If many parts begin to fall outside the tolerance specifications, then immediate action must be taken to correct a deficiency in the process that is responsible for the discrepancy.

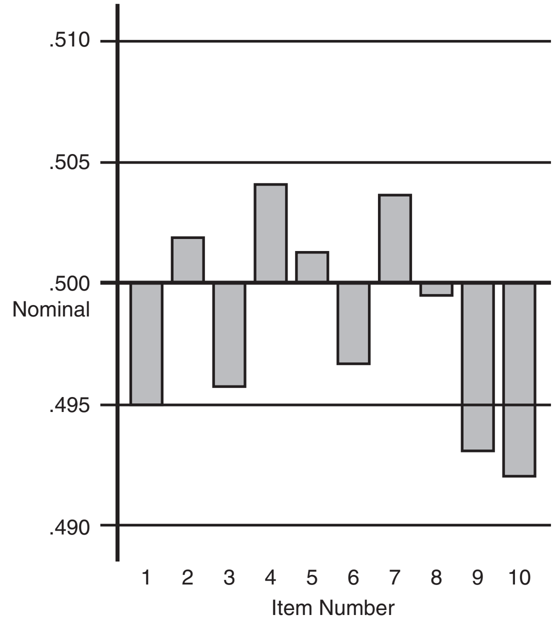


Figure C-262 Measuring equipment for SPC can generate various types of bar, line, and scatter graphs showing part dimension distributions and other statistical data.

Figure C-263 The digital caliper is an example of SPC equipment for dimensional measurement of machined parts. The attached microprocessor records, graphs, and prints part dimensions and generates appropriate statistical data (*Mitutoyo America Corp.*).

Tools for SPC

The advent of the microprocessor has permitted the development of many useful tools for SPC. For SPC functions in machining manufacturing, these measuring instruments look much the same as their conventional electronic counterparts and include calipers, micrometers, depths gages, and dial indicators (Figures C-263 and C-264). SPC equipment also includes microcomputers and suitable software able to perform a variety of SPC functions and to generate the appropriate statistical data.

By interfacing the measuring equipment with a microprocessor and suitable software, statistical data can be recorded, graphed, and then analyzed. The programmable capability of the SPC microprocessor allows various parameters to be preset for a given inspection task. For example, the computer may be programmed with the high and low tolerance limits of parts. As parts are produced and inspected by the attached electronic gaging device, statistics are generated immediately. These include maximum and minimum size, average size, and deviations of tolerance specifications from acceptable norms. SPC computer systems and software have the capability to record and compile statistical data for

Figure C-264 The outside micrometer is another example of SPC equipment for dimensional measurement. The data module records, graphs, and prints part dimensions and generates statistical data (*Mitutoyo America Corp.*).

many different part specifications as well as from many different processes in the same or different manufacturing facilities. PC microcomputers, minis, or mainframes can accept data from different inspection stations or over local area computer networks (LANs). The computer system can then generate SPC reports for screen viewing, printouts, or permanent computer memory storage.

Role of the Machinist in SPC

Every machinist has a personal responsibility to produce machined parts that are within specified tolerances. In this capacity, some of your work may require that you inspect parts made by a production machine, using SPC tools such as those discussed, that both measure and generate statistical information about part dimensions. If the machining process that you are running is not producing parts to acceptable tolerances, you may also be responsible for determining the cause of the problem and providing corrective actions, by making appropriate adjustments to feeds, speeds, and cutting tools.

SELF-TEST

1. Why are tolerances important in manufacturing?
2. What are typical standard tolerances?
3. Name three geometric specifications called out on drawings.
4. What is the general rule for press fit allowances?
5. Describe shrink and expansion fits.
6. Describe SPC tools and activities.
7. What is the difference between bilateral and unilateral tolerance?
8. Explain high and low limit tolerances.
9. For the dimension 2.467 + .001 − .003, what would be the largest acceptable in-tolerance size?
10. Explain overlapping tolerances.