ASME B89.1.6-2002
(Revision of ASME B89.1.6M-1984)

REAFFIRMED 2012

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MEASUREMENT OF PLAIN INTERNAL DIAMETERS FOR USE AS MASTER RINGS OR RING GAGES

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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The American Society of Mechanical Engineers

A N   A M E R I C A N   N A T I O N A L   S T A N D A R D

MEASUREMENT OF PLAIN INTERNAL DIAMETERS FOR USE AS MASTER RINGS OR RING GAGES

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(Revision of B89.1.6M-1984)

Date of Issuance: December 31, 2003

This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda or written interpretations of the requirements of this Standard issued to this edition.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

The American National Standards Committee B89 on Dimensional Metrology was established in February 1963 under the sponsorship of the American Society of Mechanical Engineers. The first organization meeting was held at the United Engineering Center in New York City. The scope of the Committee was defined as follows:

Calibration and the specific conditions relating thereto. It shall encompass the inspection and the means of measuring the characteristics of the various geometrical configurations such as lengths, plane surfaces, angles, circles, cylinders, cones, and spheres.

Among the six Subcommittees originally established to carry out this mandate was B89.1 - Length, whose chairman authorized the formation of B89.1.6 to prepare a standard on the measurement of internal diameters for use as master rings and ring gages. The standard was approved by ANSI as an American National Standard on June 10, 1976.

The B89 Committee was reorganized as an ASME Standards Committee on July 8, 1981. The ASME B89 Committee revised the Standard which included specifications that extend qualifications of rings up to 21 in. (533 mm), consolidated information into tables from within the original standard and from other sources, and related surface texture to tolerance rather than class. The revised Standard was approved by the American National Standards Institute on June 18, 1984.

In October of 1997, the B89.1.6 Committee began rewriting and revising the Standard because of many advances in measurement technology and standardization among laboratories both in the United States and abroad. Several changes have been made to the Standard to reflect a more up-to-date approach to internal diameter measurement, and to include information needed by laboratories for purposes of standardization, accreditation, etc. This revision was approved by the American National Standards Institute on October 29, 2002.

ASME B89 COMMITTEE
Dimensional Metrology

(The following is the roster of the Committee at the time of approval of this Standard.)

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General. ASME Codes and Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016

Proposed Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible: citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Attending Committee Meetings. The B89 Standards Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the Secretary of the B89 Standards Committee.

MEASUREMENT OF PLAIN INTERNAL DIAMETERS FOR USE AS MASTER RINGS OR RING GAGES

1 SCOPE

This Standard is intended to establish uniform practices for the measurement of master rings or ring gages using horizontal methods. The standard includes requirements for geometric qualities of master rings or ring gages, the important characteristics of the comparison equipment, environmental conditions, and the means to assure that measurements are made with an acceptable level of accuracy.

This Standard does not include measurement methods for rings below 1 mm (0.040 in.). The measurement method on these very small rings should be agreed upon prior to manufacture or calibration between the manufacturer/laboratory and customer.

2 DEFINITIONS

bilateral tolerance: application of one half of the tabulated tolerance plus and minus from the specified size.

circularity (roundness): circularity is a condition of a surface of revolution where:

(a) for a cylinder or cone, all points of the surface intersected by any plane perpendicular to a common axis are equidistant from that axis

(b) for a sphere, all points of the surface intersected by any plane passing through a common center are equidistant from that center

cosine error: the measurement error in the measurement direction caused by angular misalignment between a measuring system and the gage or part being measured.

cylindricity: cylindricity is a condition of a surface of revolution in which all points of the surface are equidistant from a common axis.

diameter: the length of a straight line through the center of a circular cross-section of an object. In the case of a cylinder, the line is considered to be perpendicular to the axis.

dimensional stability: ability of an object (e.g. measuring instrument or work piece) to maintain its metrological characteristics with time.

NOTES:
(1) Where stability with respect to a quantity other than time is considered, this should be stated explicitly.
(2) Stability may be quantified in several ways, for example: in terms of the time in which a metrological characteristic changes by a stated amount, or in terms of the change in a characteristic over a stated time.

discrimination (threshold): largest change in a stimulus that produces no detectable change in the response of a measuring instrument, the change in the stimulus taking place slowly and monotonically.

elastic deformation: the non-permanent (reversible) change in the size or geometry of a part due to an applied force.

gage block: a length standard with rectangular, round or square cross section, having flat, parallel opposing gaging faces.

NOTE: The surface finish of the gaging faces should be such as to allow gages to be wrung together.

Go ring: an internal diameter gage manufactured to the part tolerance high limit with a unilateral minus tolerance, therefore accepting the manufactured part when in size.

index of refraction: for a given wavelength, the ratio of the velocity of light in a vacuum to the velocity of light in a refractive material.

NOTE: As used in this Standard, the material is air.

line contact: the zone of contact between a flat surface and a cylinder.

lobing: systematic variations in the radius around a part (measured in the cross section perpendicular to the axis).

master ring: an internal diameter standard used to set other gaging equipment. Master rings are manufactured to a bilateral tolerance.

max. (maximum) master ring: an internal diameter standard used to set other gaging equipment. Max. master rings are manufactured to a unilateral *Minus* tolerance on the part tolerance high limit.

mean master ring: An internal diameter standard used to set other gaging equipment. Mean master rings are manufactured to a bilateral tolerance.

measurand: measurement of a well defined physical quantity.

Example: Diameter of a cylindrical gage at 20°C.

measurement force: the amount of force exerted upon the object being measured by a measuring instrument during the act of measurement. Measurement force is an important factor used in the calculations of elastic deformation.

microinch: one millionth of an inch, i.e., 0.000001 inch, 1 μin., or 25.4 nanometers.

micrometer: one millionth of a meter, i.e., 0.000001 meter, 1 μm, or approximately 39.37 microinches.

min. (minimum) master ring: an internal diameter standard used to set other gaging equipment. Min. master rings are manufactured to a unilateral *Plus* tolerance on the part tolerance low limit.

modulus of elasticity: the ratio of unit stress to unit deformation for a particular material, within the limit of proportionality, i.e., $E = \sigma/\varepsilon$.

NOTE: The modulus of elasticity is sometimes known as Young's modulus.

NoGo ring: an internal diameter gage manufactured to the part tolerance low limit with a unilateral plus tolerance, therefore accepting the manufactured part when in tolerance by not fitting on the part.

nominal coefficient of thermal expansion: approximate value (ISO VIM: 1993 Section 5.3) for the coefficient of thermal expansion over a range from a temperature, T, to 20°C and denoted α_n for the part and α_{ns} for the reference standard. Estimated values for α_n and α_{ns} may be obtained from experiments on like objects or from published data.

out-of-roundness: is the term used to describe a deviation from being round and its value is defined as the minimum radial separation between two concentric circles within which all points on the circular cross section lie.

out-of-straightness: the deviation of the straightness of a line is the minimum distance between two parallel lines, which contain the line profile.

point contact: the single point of contact when using a sphere or section of a sphere in a measurement.

NOTE: The idealized point becomes an area of contact under the measurement force.

Poisson's ratio: the ratio of the transverse unit deformation of a body to the unit deformation in length, within the limit of proportionality.

ring gage: an internal diameter standard used for setting other measuring instruments or checking the manufactured parts as Go/NoGo gages.

roundness: (see circularity).

resolution (of a displaying device): smallest difference between indications of a displaying device that can be meaningfully distinguished.

NOTES:
(1) For a digital displaying device, this is the change in the indication when the least significant digit changes one step.
(2) This concept applies also to a recording device.

straightness: the minimum distance between two parallel lines which contain the line profile.

surface texture: repetitive or random deviations from the nominal surface, which form the pattern of the surface. Surface texture includes roughness, waviness, lay and flaws.

taper: for the purposes of this Standard, taper is defined as the gradual increase or decrease in diameter over the full length of the gage.

thermal gradients: the rate of change of temperature as a function of another parameter.

NOTES:
(1) Temporal thermal gradient is the variation of temperature as a function of time, denoted by $\Delta T/\Delta t$, °C/hour (or °F/hour).
(2) Spatial thermal gradient is the variation in temperature as a function of length, denoted by $\Delta T/\Delta L$, °C/m (or °F/in.).

uncertainty of measurement: parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES:
(1) The parameter may be, for example, a standard deviation (or a given multiple of it), or the half width of an interval having a stated level of confidence.
(2) See NIST Technical Note 1297 for additional information.

unilateral tolerance: the entire gage tolerance is applied unidirectionally at the extreme limits of the part tolerance. This applies to Go/NoGo min./max. ring gages.

3 REFERENCES

The following is a list of publications referenced in this Standard.

ANSI/ASME B47.1, Gage Blanks
Publisher: American National Standards Institute (ANSI) 25 West 43rd Street, New York, NY 10036

ASME B46.1, Surface Texture (Surface Roughness, Waviness, and Lay), 1995
ASME B89.1.2M, Calibration of Gage Blocks by Contact Comparison Methods (Through 20 in. and 500 mm)
ASME B89.1.5, Measurement of Plain External Diameters for Use as Master Discs or Cylindrical Plug Gages
ASME B89.1.9, Standard Gage Blocks
ASME B89.3.1, Measurement of Out-of-Roundness
ASME B89.6.2, Temperature and Humidity Environment for Dimensional Measurement
Publisher: The American Society of Mechanical Engineers (ASME International, Three Park Avenue, New York, NY 10016-5990; Order Department: 22 Law Drive, Box 2300, Fairfield, NJ 07007-2300

ISO 1, Standard Reference Temperature
ISO Report, Guide to the Expression of Uncertainty in

Measurements

International Organization for Standardization (ISO), 1 rue de Varembé, Case Postale 56, CH-1211, Genève 20, Switzerland/Suisse

NIST Technical Note 1297, 1994 Edition, Guidelines for Evaluation and Expressing the Uncertainty of NIST Measurement Results

Publisher: National Institute of Standards and Technology (NIST), U.S. Government Printing Office, Washington, DC 20402-9325

Puttock and Thwaite, "Elastic Compression of Spheres and Cylinders at Point and Line Contact," National Standards Laboratory Technical Paper No. 25, 1969

Publisher: Commonwealth Scientific and Industrial Research Organization (CSIRO), 150 Oxford Street, Collingwood, Victoria 3066, Australia

4 REQUIREMENTS OF MASTER RINGS AND RING GAGES

4.1 General

The capability of measuring equipment and techniques to achieve a high order of precision in the calibration of master rings or ring gage is limited by relevant features and conditions of the gage to be measured. These are discussed in the following sections:

(a) 4.2 Design
(b) 4.3 Material
(c) 4.4 Surface Roughness
(d) 4.5 Geometric Requirements
(e) 4.6 Face Perpendicularity of Rings
(f) 4.7 Tolerance Classes

All dimensions and specifications given in this Standard are for gages that have not been modified. Modifications to gages through processes such as machining, grinding, stamping, etc., where heat or stress is produced can alter the measured diameter(s), and thus would invalidate a reported dimension from a measurement taken before the modification.

The minimum marking requirements for ring gages shall be the size or diameter, and tolerance class. If the tolerance does not match one of the standard classes as listed in Tables 1, 2, and 3 it does not have to be included. For rings made to tolerances other than those listed, the customer should specify the marking requirements.

4.2 Design

The design and proportion specifications for gage blanks are given in ANSI/ASME B47.1.

The ISO design is acceptable when communicated between the customer and the manufacturer. See Appendix C for ISO 3670 design specifications.

4.3 Material

The material, including coatings or wear inserts, of rings or ring gage blanks shall be free from inclusions or other imperfections, which would affect surface texture. It is desirable for the material to have approximately the same coefficient of expansion as the gage blocks to be used in order to minimize the effect of small differences in temperature. It shall respond to applicable hardening and stabilizing processes to permit finishing to the pertinent surface roughness and to assure dimensional stability. Finished surfaces should have a minimum hardness equivalent to 60 on the Rockwell C Scale. Master gages shall not be subjected to any quick aging or shock treatment as a check of stability. If the material shows magnetism, the gage should be de-magnetized before measurements are taken.

4.4 Surface Roughness

The surface roughness shall be consistent with the class tolerance of the gage. Table 1 lists maximum roughness values expressed in arithmetic average (R_a) roughness values. ASME B46.1, shall be consulted for reference information.

4.5 Geometric Requirements

4.5.1 General. The diameter will be measured per section 6 of this Standard. Typical acceptance criteria for geometric requirements are diameter measurements spaced approximately 90 deg apart in each of three planes: the midsection, and each end, located $^1/_{16}$ in. (1.6 mm) from inside the ends of corner radii or chamfers. For sizes below 0.150 in. (3.8 mm), a total of four diameter measurements should be taken in two planes within the center half of the ring.

Two-point diameter measurements will not detect the effect that odd-numbered or irregular lobing has on size. Diameter measurements taken at multiple locations may not fully detect ovality, even-numbered lobing, or straightness deviation.

The practical application of Table 3 would be to compare the measured size of a gage to the prescribed size minus (for Go or Max.) or plus (for NoGo or Min.) the tabulated tolerance (for bilateral gages, plus and minus one-half the tabulated tolerance). The measured size should fall within the size range thus specified. The practical application of Table 2 would be to compare all the measurements taken on a gage and find the difference between the largest and smallest measurements. The difference should not exceed the tabulated value.

NOTE: ASME Y14.5M RULE #1 DOES NOT APPLY DUE TO THE LIMITATIONS OF PRECISION MEASURING EQUIPMENT AND THE INABILITY TO CORRELATE COMPOSITE FORM DEVIATIONS WITH ABSOLUTE SIZE. (Perfect form at Maximum Material Condition is not required.)

Table 1 Surface Roughness Limits for Master Rings and Ring Gages

Diameter, in.		Tolerance Class, μin. (R_a) [Note (1)]					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
0.040	0.825	2 [Note (2)]	2 [Note (2)]	4	4	8	10
0.825	1.510	2 [Note (2)]	2 [Note (2)]	4	8	12	14
1.510	2.510	4	4	8	12	16	16
2.510	4.510	4	4	8	12	16	16
4.510	6.510	6	6	12	16	16	16
6.510	9.010	8	8	16	16	16	16
9.010	12.010	8	8	16	16	16	16
12.010	21.010	16	16	16	16	16	16
Diameter, mm		Tolerance Class, μm (R_a) [Note (1)]					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
1.016	20.96	0.05 [Note (2)]	0.05 [Note (2)]	0.10	0.10	0.20	0.25
20.96	38.35	0.05 [Note (2)]	0.05 [Note (2)]	0.10	0.20	0.30	0.36
38.35	63.75	0.10	0.10	0.20	0.30	0.41	0.41
63.75	114.55	0.10	0.10	0.20	0.30	0.41	0.41
114.55	165.35	0.15	0.15	0.30	0.41	0.41	0.41
165.35	228.85	0.20	0.20	0.41	0.41	0.41	0.41
228.85	305.05	0.20	0.20	0.41	0.41	0.41	0.41
305.05	533.65	0.41	0.41	0.41	0.41	0.41	0.41

NOTES:
(1) R_a shall be evaluated using Gaussian filters with $\lambda c = 0.8$ mm (0.030 in.), and a tip radius of 2 μm (80 μin.).
(2) State-of-the-art limitations decree that the method of verification be established by agreement between manufacturer and user.

4.5.2 Roundness. Deviations in roundness can be determined at three planes (see para. 4.5.1) perpendicular to the axis of the gage, using a chart type precision spindle instrument. The out-of-round condition shall not exceed the value shown in Table 2. ASME B89.3.1 shall be consulted for measurement information. Ring gages used for applications other than as diameter masters, such as limit gages, shall be evaluated by criteria applicable to the intended use, with Table 2 serving only as a reference guide.

4.5.3 Straightness and Taper. Deviations from surface element straightness can be determined by making axial tracings approximately 90 deg apart using a profile type instrument. The determined value shall not exceed the tolerances listed in Table 2. Taper is measured as the gradual increase or decrease in diameter over the full length of the gage.

4.6 Face Perpendicularity of Rings

The faces of the ring gage should be reasonably square to the Inner Diameter (ID) of the ring gage to eliminate the first order or cosine errors that arise from imperfect alignment of the measuring contacts. If the out-of-squareness is less than 50 times the total diameter tolerance (see Table 3) multiplied by the stated size of the gage, the error is small enough under ordinary circumstances to be ignored. When extremely accurate measurements are required squareness errors may need to be eliminated by means of tilt tables or mathematical compensation.

4.7 Tolerance Classes

Master rings and ring gages are graded into classes identified by XXX, XX, X, Y, Z, and ZZ which determine the total applicable tolerance for a given size. When the tolerance is applied unilaterally, the full amount of the tolerance as specified in Table 3 is applied to the stated gage size in one direction with the other direction being zero. For instance, a class X ring in the 0.040 to 0.825 range would have a tolerance of + 0.000040/− 0.0 (unilateral plus) or + 0.0/− 0.000040 (unilateral minus). When the tolerance is applied bilaterally, the tolerance specified in Table 3 is split in half and applied in both directions from the stated gage size. For instance a class X ring in the 0.040 to 0.825 range would have a tolerance of + 0.000020/− 0.000020.

Table 2 Limits for Roundness, Taper, or Straightness for Master Rings and Ring Gages

Diameter, in.		Tolerance Class, μin.					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
0.040	0.825	5	10	20	35	50	100
0.825	1.510	8	15	30	45	60	120
1.510	2.510	10	20	40	60	80	160
2.510	4.510	13	25	50	75	100	200
4.510	6.510	16	33	65	95	125	250
6.510	9.010	20	40	80	120	160	320
9.010	12.010	25	50	100	150	200	400
12.010	15.010	38	75	150	225	300	600
15.010	18.010	50	100	200	300	400	800
18.010	21.010	63	125	250	375	500	1000

Diameter, mm		Tolerance Class, μm					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
1.016	20.96	0.13	0.25	0.51	0.89	1.27	2.54
20.96	38.35	0.20	0.38	0.76	1.14	1.52	3.05
38.35	63.75	0.25	0.51	1.02	1.52	2.03	4.06
63.75	114.55	0.33	0.64	1.27	1.91	2.54	5.08
114.55	165.35	0.41	0.84	1.65	2.41	3.18	6.35
165.35	228.85	0.51	1.02	2.03	3.05	4.06	8.13
228.85	305.05	0.64	1.27	2.54	3.81	5.08	10.16
305.05	381.25	0.97	1.91	3.81	5.72	7.62	15.24
381.25	457.45	1.27	2.54	5.08	7.62	10.16	20.32
457.45	533.65	1.60	3.18	6.35	9.53	12.70	25.40

GENERAL NOTE: Any single geometric error, such as those outlined in Table 2, roundness, taper, or straightness shall not exceed the listed values. The tabulated values are one-half of the total diameter tolerance applicable for the class of gage.

4.8 Identification

Unless otherwise specified, ring gages identified as Go or NoGo are assumed to be gages used to measure the limits of a product. The Go gage is the larger, taken from the specified maximum diameter of the product, and has the tolerance applied unilaterally minus. The NoGo gage is the smaller, taken from the specified minimum diameter of the product, and has the tolerance applied unilaterally plus.

Gages identified only with the size are assumed to be master gages with a bilateral tolerance. Master gages are reference gages and can take many forms based on the application. Some manufacturers and users will always assume that a designation of Master ring has the tolerance applied bilaterally. Others will ask for more information to clarify the tolerance application. Commonly used assumptions for designations and tolerance applications are: Max. or Maximum Master (unilateral minus tolerance), Min. or Minimum Master (unilaterally plus tolerance), and Mean Master (bilateral tolerance).

There is no substitute for good communication between the user and the manufacturer for determining the correct application of the tolerance of the gage based on its intended use.

5 CALIBRATION OF AN IDENTIFIED DIAMETER

5.1 General

Internal diameters shall be measured in a manner consistent with sound metrological principles. An associated measurement uncertainty shall accompany each measurement. Some acceptable methods are described in this section.

5.2 Location of Calibrated Diameter

The location of the measurement points as given in para. 4.5.1 shall be identified on the gage face by means of the orientation of the marking or by scribed lines. The marking of the size shall be oriented as it would be read, and the zero degree or X axis would be horizontal, with the 90 deg or Y axis being vertical. If scribed lines are marked on the face, they shall be for the zero degree or X-axis as shown in Fig. 1.

5.3 Contact Force

In a comparison type of measurement where the master has the same shape, material, and surface texture as the work piece, contact force deformations are equal and therefore cancel out as a factor in the measurement process. However, when comparing flat surfaces (such

Table 3 Diameter Tolerances for Classes and Sizes for Master Rings and Ring Gages

Diameter, in.		Tolerance Class, μin.					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
0.040	0.825	10	20	40	70	100	200
0.825	1.510	15	30	60	90	120	240
1.510	2.510	20	40	80	120	160	320
2.510	4.510	25	50	100	150	200	400
4.510	6.510	33	65	130	190	250	500
6.510	9.010	40	80	160	240	320	640
9.010	12.010	50	100	200	300	400	800
12.010	15.010	75	150	300	450	600	1200
15.010	18.010	100	200	400	600	800	1600
18.010	21.010	125	250	500	750	1000	2000
Diameter, mm		**Tolerance Class, μm**					
Above	To and Including	*XXX*	*XX*	*X*	*Y*	*Z*	*ZZ*
1.016	20.96	0.25	0.51	1.02	1.78	2.54	5.08
20.96	38.35	0.38	0.76	1.52	2.29	3.05	6.10
38.35	63.75	0.51	1.02	2.03	3.05	4.06	8.13
63.75	114.55	0.64	1.27	2.54	3.81	5.08	10.16
114.55	165.35	0.84	1.65	3.30	4.83	6.35	12.70
165.35	228.85	1.02	2.03	4.06	6.10	8.13	16.26
228.85	305.05	1.27	2.54	5.08	7.62	10.16	20.32
305.05	381.25	1.90	3.81	7.62	11.43	15.24	30.48
381.25	457.45	2.54	5.08	10.16	15.24	20.32	40.64
457.45	533.65	3.18	6.35	12.70	19.05	25.40	50.80

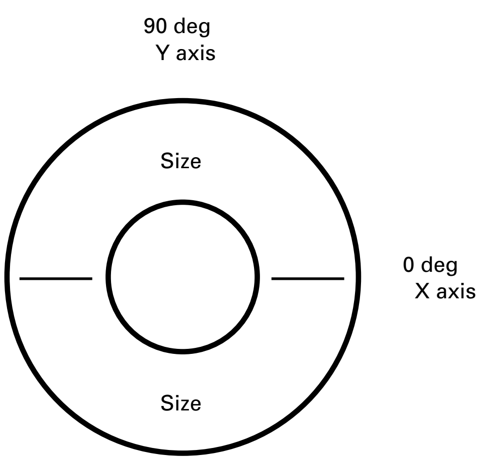

Fig. 1 Location of Calibrated Diameter

as gage blocks) and the internal surface of a master ring, there can be a significant difference as the radius of the ring approaches the radius of the contact. Contact force can create compressive deformation of the contact surface and bending of cantilever type fingers. To minimize contact force deformation in these cases, the lightest gaging force should be used. It is recommended that no more than 2 oz. (56.7 g) gaging force be used for a probe radius of 0.016 in. (0.41 mm) and no more than 4 oz. (113.4 g) for a probe radius of 0.060 in. (1.52 mm) to avoid any permanent deformations. Differences in deformation at the contact surfaces may be significant to measurement results when the ratio of the contact radius to the master ring radius is greater than 1:4.

When measuring ring gages on instruments where the ring is not free to float in the axis of measurement, it is recommended to support the ring on anti-friction rolls. This will minimize the friction force between the ring and the resting surface of the instrument. If this is not done, the ring may bend the measuring fingers unequally. Unless the reference combination bends the fingers in exactly the same way, this will generate errors in the measurement.

5.4 Tilt Tables

When a ring gage is being measured on a machine that uses the top or bottom of the ring as a reference surface, perpendicularity error exists. This error can be relatively small depending on the geometry of the reference surface in relation to the internal cylinder wall of the ring gage. This error produces a cosine error in the measurement of the ring gage. A tilt table may be used to eliminate such error. A tilt table allows the user to align the machine's measuring jaws to the perpendicular centerline of the internal cylinder walls of the ring gage. Table 4 gives examples of squareness and cosine error relationships that occur with a 1 in. diameter ring gage.

Table 4 Face Squareness Error/Cosine Error Relationship

Squareness Error			Cosine Error	
in.	mm	Angle [Note (1)]	μin.	μm
0.0001	0.0025	0 ft 10 in.	0	0
0.0005	0.0127	0 ft 52 in.	0.13	0.0033
0.001	0.0254	1 ft 43 in.	0.50	0.0127
0.005	0.1270	8 ft 36 in.	12.50	0.3175
0.010	0.2540	17 ft 11 in.	50.0	1.27

NOTE:
(1) Variation in minutes and seconds in perpendicularity between table top and ring diameter being measured.

5.5 Measurements Using a Mechanical Comparator

Master rings or ring gages are usually measured by comparing them to a reference master ring, a single gage block, or a combination gage block stack. The method of comparing a ring gage to master artifacts consists of measuring the displacement of one or both contacts that touch the gage. Using gage block(s) or master rings of the same material as the gage being measured will minimize variations due to differences in contact deformation and due to differences in the nominal coefficient of thermal expansion. See para. 6.4. To achieve optimum accuracy when using gage blocks, the calibrated value of each gage block in the stack shall be summed, then used in the measurement process.

Due to limitations in accessing the inside gaging surface of internal diameter artifacts, a spherical probe is the only contact geometry that can be used for high accuracy comparison measurements. Care must be taken to periodically check for wear or flats on the contact surface. This can be accomplished by a procedure of checking a known size ring gage to a known size gage block stack.

Comparison measurements of ring gages are generally two-point measurements. Two-point diameter measurements will not detect the effect that odd-numbered lobing will have on the size.

First, verify that the comparator is set sensitive to internal diameter measurements. Second, verify that the probe diameters are smaller than the internal diameter of the ring.

Comparator instruments can generally be categorized as either short range or long range (commonly known as direct reading instruments). Each has distinct advantages and disadvantages.

Short range comparators require a master artifact of the same size as the diameter being measured. The effects from instrument geometry, alignment, scale, motion errors, and most of the thermal effects are minimized if the change in temperature is not short term. Short range comparators generally use an LVDT to detect displacement between the measuring probes.

Direct reading instruments generally allow a large measuring range and measure diameters of all sizes within the range. Direct reading instruments contain transducers such as laser interferometers, glass scales, holographic scales, and others. For direct reading instruments, instrument alignments and motion errors may become an important source of measurement uncertainty. These instruments are often set up using several ring gages of known diameter to calibrate the scale magnification. These errors are then commonly assumed to be linear between these set points throughout the measurement range. Calibration in this manner reduces the number of artifacts needed for the measurement of diameters. Direct reading instruments can also be used as comparators in which master rings or ring gages are measured by comparing them to a reference master ring, a single gage block, or a combination gage block stack.

Comparator instruments that measure internal diameter can have either one sphere or two opposing spheres as contact probes. Each configuration has advantages and disadvantages. The mastering artifact, being either a master ring or an assembly of gage blocks, can also affect the performance of the comparator. These configurations will be discussed individually.

5.5.1 Dual Sphere Contact Probe Configuration. The most common configuration is a dual-sphere contact probe configuration. The spherical probes are mounted on stems or fingers that allow the probes access into the bore of the ring. These fingers are connected to a sensor that measures the displacement of the finger(s) during measurement.

When comparing artifacts with this probe configuration, bending effects of the probe stems or fingers can be overcome if the probe forces are applied in the same direction and with the same magnitude for each artifact measurement. The bending is then common in each measurement and the effects cancel. This measurement is the axis of the ring bore at that particular point down the bore. Effects resulting from non-perpendicularity of the bore to the bottom surface and comparing the results. Differences indicate the ring bore is not perpendicular to the bottom of the ring across the measurement plane.

5.5.1.1 Mastering to a Ring Gage. Comparing rings gages of the same nominal size is a classic, common artifact comparison measurement. The effects from instrument geometry, alignment, scale, motion errors, and most of the thermal effects are minimized when comparing rings of the same nominal size. Elastic deformation corrections can be ignored if the elastic constants of both the master ring and the test ring are the same.

The measurement datum can vary depending on the design of the comparator. Depending on the geometry of the ring gage, different datums will yield different measurement results. Some instruments use a gage support table that can be translated horizontally but unable to tilt. For these instruments, the measurement datum becomes the bottom surface of the ring gage and results in a measurement plane that is parallel to this surface. Non-perpendicularity of the ring bore to the bottom of the ring will result in a diameter measurement larger than the actual diameter perpendicular to the bore.

On instruments with gage support tables that tilt, the ring gage can be tilted until the minimum diameter across the bore is achieved. The measurement datum of the ring can be measured by rotating the ring 180 deg because when positioning the master ring on the comparator, adjust the position until the maximum diameter across the bore is seen on the comparator analog or digital display. This can be done using the horizontal adjustments on the gage support table or by tapping the ring lightly. This setup is repeated for measurements of the test ring.

For direct reading instruments, the ring gages being measured are often of dissimilar size from those used to set up the instrument magnification. Therefore, local air and gage temperatures should be monitored to determine correction values for the thermal expansion of the instrument scale and the ring gages. Depending on the required accuracy, elastic deformation corrections may need to be made for each ring gage. Calculations can be computed using equations from Puttock and Thwaite's CSIRO Technical Paper No. 25.

5.5.1.2 Mastering to a Gage Block Assembly. When comparing ring gages to a gage block stack using a dual probe comparator, the gage block stack must be constructed for an inside measurement. This requires that the stack, built to the nominal size of the ring gage to be measured, use end pieces to facilitate the internal measurement condition. Some examples of this are shown in Fig. 2.

The gage block setup technique shown in Fig. 2(a) can be used for any size ring. For large rings (greater than 50 mm) this can be the preferred arrangement. The stack is rested on its side and is positioned on the comparator with the probes between the end pieces. The stack is then tapped and rotated around the probes until a minimum value is indicated on the display. Note that this arrangement uses the non-gaging surfaces of the gage blocks as the datum surface. The perpendicularity of the end pieces to the gage support table can be compromised with this arrangement. This can be a larger problem for multiple block stacks where this side surface is likely to be uneven. Also, flatness and parallelism errors of the gage blocks can be magnified as the stack length is projected out with the end pieces.

The technique used in Fig. 2(b) uses a precision square as one end piece and a base for the assembly. This setup should insure the perpendicularity of the gage block stack to the support table, however the gage block geometry errors can still be magnified with the remaining end piece. This arrangement also becomes unstable and tilts as the combination length exceeds 50 mm.

The technique shown in Fig. 2(c) can result in very large measurement errors if not constructed properly. This arrangement is typically used with square gage blocks that have a hole bored through the center. After the large end pieces are wrung to each end of the stack a threaded rod can be inserted through the entire assembly, which can be a useful feature for very long gage block stacks. The clamp nuts on the ends of the tie rods must be only very lightly finger tight or compression of the assembly will occur and large measurement errors will result. One advantage of this arrangement is that the large end pieces allow for the measurement to be performed on either end of the stack. This feature can be used to check the parallelism of the gage block combination.

Depending on the required accuracy, elastic deformation equations may be required for the combination and the ring gage even if they are of the same material. For larger ring sizes, these differences are generally small. Large differences, 50 nanometers and more, can result when measuring small rings where the probe's diameter approaches the size of the ring diameter. As usual, dissimilar material comparisons do require deformation corrections. Calculations can be computed using equations from Puttock and Thwaite's CSIRO Technical Paper No. 25.

5.5.2 Single Sphere Contact Probe Configuration. Some instruments may only use a single spherical probe to perform the comparison measurement. As in the dual probe techniques, the sphere must also be mounted on a stem to allow access into the ring bore. The bending of this stem during measurement can be overcome as before, if the probing forces are applied in the same direction and with the same magnitude for each artifact.

Appropriate fixturing of the artifacts is required for single probe systems because during measurement the probe force in one direction is not offset by the second probe, and the measurement is invalidated if the ring moves. The fixturing must hold the ring in place but not deform the shape of the gage. Over-restraining the master or test gages will result in large measurement errors.

Depending on the measuring instrument design and the protocols followed during the ring gage measurement, several measurement datums are available. For example, the ring bore can be probed and an average datum axis can be developed. To avoid cosine errors when measuring with single probe instruments, the plane of motion used by the instrument must be either parallel (if the ring bore is used) or perpendicular (if the top or bottom surface of the ring is used) to the datum chosen for the ring gage.

Single probe instruments are generally a 1D direct reading instrument as described above or a 3D instrument such as a coordinate measuring machine (CMM).

5.5.2.1 Mastering to a Ring Gage. When using small 1D comparator instruments, positioning the ring gages

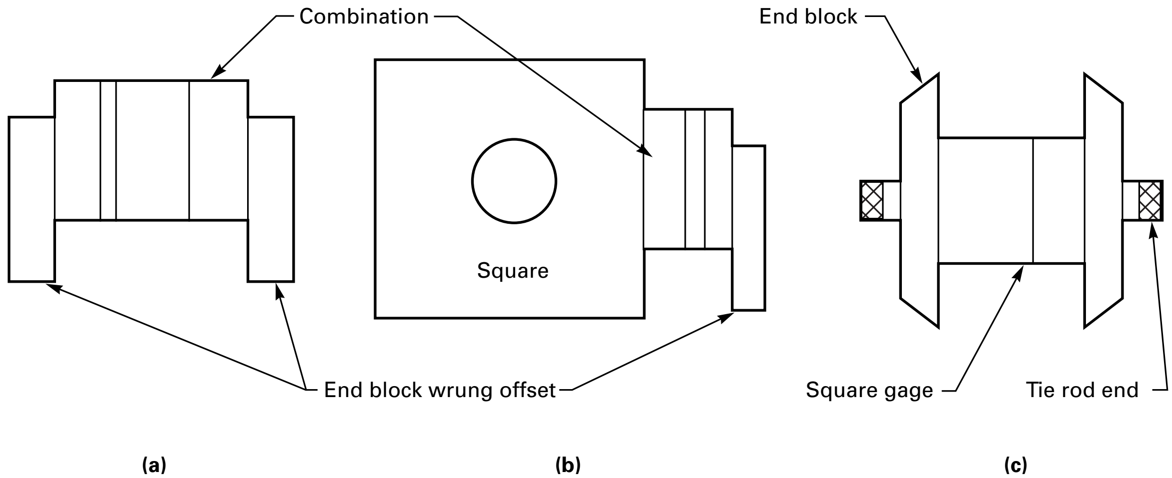

Fig. 2 Typical Gage Block Combination Techniques for Ring Gage Measurements

so the maximum diameter is probed by the instrument is more difficult than with a dual probe system. When mastering to another ring gage, the bending of the probe stem is common in each measurement as long as the applied force is the same for each ring. Also, as before, elastic deformation corrections can be minimized if the elastic constants of both the master ring and the test ring are the same.

For larger 3D instruments, both the master ring and test ring can generally be placed on the gage support table together. For this configuration, the chosen datum should be the same for each ring. To reduce the effects of unknown errors in the instrument motion, the master ring can also be removed and the test ring placed in the same location on the table. Instrument motion errors will then generally be the same for each measurement, however the thermal environment around the instrument and the ring gage may have been disturbed and normalizing time may be required.

In some cases, using 3D machines may be the only practical option for measuring very large rings. In any case, a careful analysis of the measurement uncertainty should be done to show that the process will yield an acceptable measurement uncertainty.

5.5.2.2 Mastering to Gage Blocks. Mastering to gage blocks with single probe systems can be done in two ways. First, the gage block stack can be built using end pieces in the same configurations shown in Fig. 2. The bending effect of the probe stem is then eliminated as described earlier.

Second, the stack can be used without end pieces. For 1D instruments, the probe would need to be lowered to move from one end of the combination to the other. These extra motions may disrupt the measurement and is not recommended.

For larger 3D instruments, the probe can more easily be moved out away from the block between either end of the stack. This technique has the advantage of reducing the effects of block geometry through the end pieces and is generally a less complicated gage block arrangement.

However this technique can have one large disadvantage. The probe stem will bend or deflect during measurement. If a probe ball of known diameter is used and the stem bending has not been calculated, a large error may result. The gaging motion when touching the gage block stack is in the opposite direction than when gaging the ring. Therefore the bending of the probe stem does not cancel. In fact, after completing the comparison measurement, the resulting error is four times the size of the bending effect. Most stylus calibration techniques used on CMM's bypass this potential error by including the stem bending into the calculation of effective probe ball diameter.

5.5.3 Non-Contact Measurement Issues. Some direct reading or absolute instruments may use laser incidence or grazing technologies to determine the diameter of ring gages. These instruments can be sensitive to the roughness or finish of the gaging surfaces and have only a limited useful measuring range. However, because these types of instruments are non-contacting, concerns over elastic deformation corrections, probe diameter measurements, or stylus bending are eliminated.

6 ENVIRONMENT

6.1 General

All environmental factors shall be controlled to achieve repeatability and accuracy as required in the measurement of master rings and ring gages.

This section contains only essentials for a metrology laboratory concerned with calibration of master rings and ring gages.

6.2 Cleanliness

Areas where calibration is performed shall be shielded from smoke, dust, mist, and other contaminants typical of some production areas. During calibration, the instrument, master, and cylinder shall be clean.

6.3 Vibration

Excessive vibration has serious detrimental effects on the accuracy attainable in precise measurements. Objectionable vibrations take two different forms and may be constant, periodic, or random in occurrence. These two forms are tactile and audible. Tactile vibrations (feel) are objectionable because they may cause inconsistent and unstable contact at the point of measurement and instability in the readout of the amplifier. Audible vibrations (noise) are objectionable if they adversely affect the performance of the operator. Following are the most common methods to bring vibration levels to acceptable values:

(a) When locating the metrology laboratory, avoid areas adjacent to, or affected by, heavy machinery, internal, or external traffic.

(b) Insulate the areas from known potential sources of vibration and use insulating mountings when installing sensitive apparatus.

(c) Create an acceptable, low operational noise level and require strict observance of it at all time.

6.4 Temperature

The standard reference temperature for industrial length measurements is fixed at 20°C (68°F) see ISO 1. The ambient temperature of the measurement area shall be controlled close to the reference temperature if accurate measurements are required.

While it is never possible to control the ambient temperature to exactly 20°C, the degree of control shall be consistent with the required accuracy of the measurements. If the master and the test parts are of the same material, a larger deviation from the nominal temperature can be tolerated than if the master and test parts are of different materials. Even when the master and test part are of the same material, care shall be taken to insure that the two items are at nearly the same temperature. If a part is brought from a 23°C shop environment into a 20°C metrology laboratory, adequate time shall be allowed for the part to reach temperature equilibrium. The use of soaking plates and thermal shielding can help equalize the temperature between the two parts.

To minimize measurement errors it will be necessary to allow both the ring and its reference combination to be together in the same thermal environment for several hours, as massive parts take considerable time to come to thermal equilibrium with their environment. When moving the reference combination or the ring from the heat sink to the measuring instrument, it is recommended to wait long enough to be sure that the artifact has come into thermal equilibrium with the gage before taking a measurement. It may take a significant time for this to occur, even if the temperature differences are only a few tenths of a degree.

In measuring rings it is critical that the combination and the ring be at the same temperature. Assuming that both the ring and the gage blocks are steel, with a coefficient of thermal expansion of 6.4×10^{-6}/°F (11.5×10^{-6}/°C), a difference in temperature of approximately 1°F (0.5°C) between a Class XXX ring and its combination will account for a significant percentage of the tolerance. For a Class XX ring the corresponding temperature difference is 2°F (1°C); for a Class X ring, 4°F (2°C); for a Class Y ring, 6°F (3°C).

Even when care is taken to insure the items are at nearly the same temperature and corrections are made to correct the temperature of the items to the reference temperature of 20°C, errors will result if the ambient temperature is far from the nominal 20°C. The errors will result from uncertainties in the coefficient of linear expansion. The change in length (ΔL) of a part with length L is

$$\Delta L = \alpha(L)\ (t - 20)$$

where

α = is the nominal coefficient of linear expansion
t = is the temperature of the part

The value of the coefficient of linear expansion is not known any better than about 10%. In a measurement area maintained at 23°C, an error of 0.23 μm (9 μin.) could result, solely from the uncertainty in the value of the coefficient, if a 25.4 mm (1 in.) cylinder is measured by comparing it to a gage block of the same material.

Further refinement can be achieved by determining the temperature of each pertinent component and applying the necessary corrections. For optimum accuracy, a thermometer can measure the parts and corrections made to compensate for the difference in temperature from master to test piece. A detailed discussion of the effects of making measurements at temperatures other than at 20°C is given in ASME B89.6.2.

6.5 Humidity

It is recommended that relative humidity in the measuring environment not exceed 45%. Humidity significantly beyond that value may cause problems with corrosion of iron or steel surfaces. Also, caution shall be used when establishing the low limit due to static electricity.

6.6 Illumination

The four factors of "vision" are brightness, size, contrast, and time. Variations in one factor may affect one or all of the others. Increasing brightness lets the eyes see small objects. However, this brightness may lessen the contrast and make it difficult or impractical to read fine scale graduations.

The proper level of illumination must be provided to accomplish each specific measurement task but will vary depending on the measurement methodology. For example, low lighting is usually used for interferometry. Supplemental illumination or illumination level controls should be available if required for specific tasks or methodologies.

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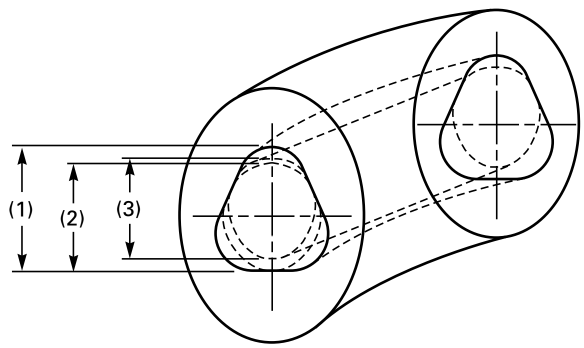
NONMANDATORY APPENDIX A
EFFECTS OF FORM AND FORM ERRORS ON SIZE (GEOMETRY)

A1 INTRODUCTION

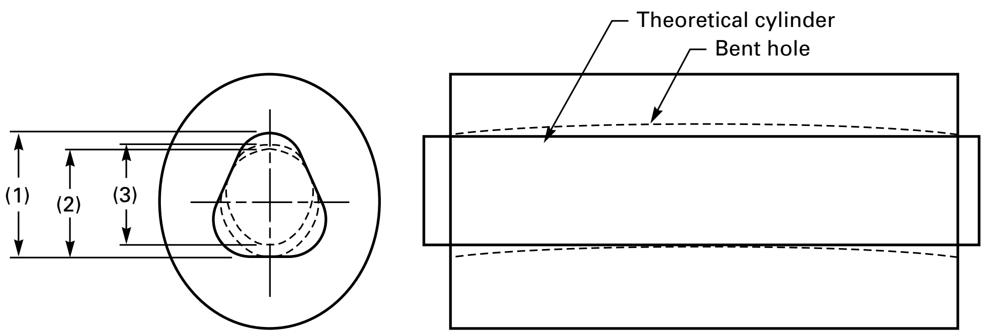
In this appendix we discuss a number of typical geometry errors of internal cylinders and how they affect the measured diameter for different measurement methods. An understanding of these interactions between form errors and measurement methods is important in choosing the most appropriate measurement method.

Figures A1, A2, and A3 present a number of examples of various form errors and how they affect the measured size and how they can be detected.

Table A1 presents the appropriate measurement method(s) for a few common form errors. Tables A2, A3, and A4 present a number of examples of how form errors affect the actual usage of ring gages when various form errors are present. Table A5 shows the relation of machining practices on the number of lobes typically found in the part form.

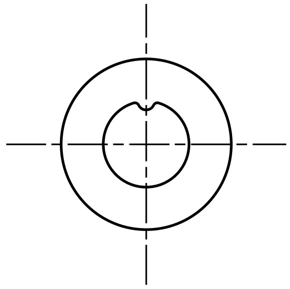


NOTES:
(1) Actual Local Size One-Dimensional Distance. As measured with a two-point device at any measuring plane.
(2) Local Mating Diameter Two-Dimensional Circle. Maximum inscribed circle at any measuring plane (This is the size of a plug that could enter this ring).
(3) Actual Mating Size Three-Dimensional Envelope. Maximum inscribed cylinder encompassing entire part (This is the size of a plug whose full length could pass through).

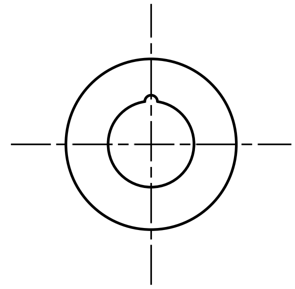


GENERAL NOTES:
(a) Difference between 1 and 2 is the roundness deviation.
(b) Difference between 2 and 3 is the straightness deviation.

Fig. A1 Analysis of a Tri-lobed and Cambered Ring Gage

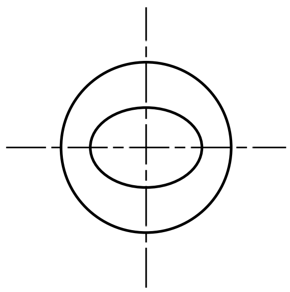


Condition A
(Single flat, burr, bump, rust)



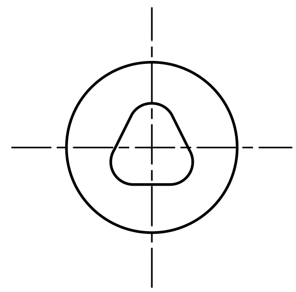
Condition B
(Single groove)

Diameter effect = 1X roundness deviation
(Directly measurable with two-point measuring device)



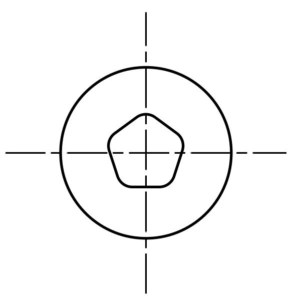
Condition C
Uniform oval or regular even numbered lobing

Diameter effect = 2X roundness deviation
(Directly measurable with a two-point measuring device)



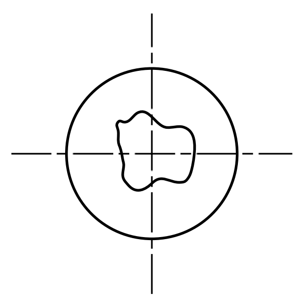
Condition D
Uniform tri-lobe

(Not directly measurable
with a two-point measuring device)



Condition E
Uniform odd-number lobing
greater than 3 lobes

Diameter effect = 1X roundness deviation
(Not directly measurable with a two-point
measuring device)



Condition F
Non uniform lobing

Diameter effect = between 1X
and 2X roundness deviation.
(May be partially measurable with a
measuring device)

Fig. A2 Form Influences on Circular Size

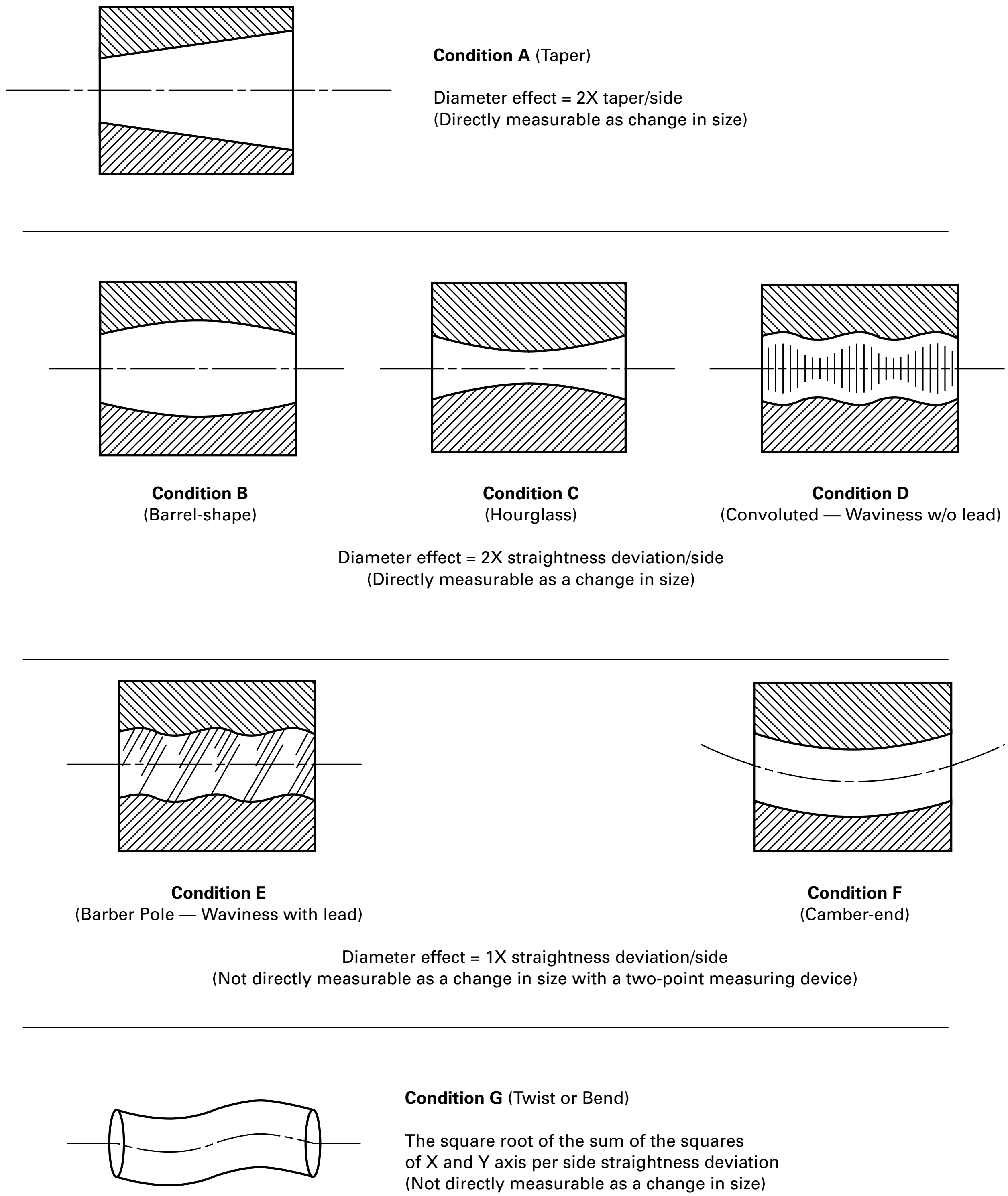


Fig. A3 Form Influences on Cylindrical Size

Table A1 Detection of Gage Form Errors
Deviation From True Cylindrical Form

Type of Form Error	Figures	Appropriate Measurement Method 1 [Note (1)]	2 [Note (2)]	3 [Note (3)]	4 [Note (4)]	5 [Note (5)]
Roundness						
Single flat	A2-Condition A	X			X	X
Single groove	A2-Condition B	X			X	X
Ovality	A2-Condition C	X			X	X
Tri-lobed	A2-Condition D				X	X
Odd numbered lobes	A2-Condition D, E				X	X
Irregular lobes	A2-Condition F	X			X	X
Taper	A3-Condition A	X	X	X		X
Straightness						
Barrel shaped	A3-Condition B	X		X		X
Hourglass	A3-Condition C	X		X		X
Convoluted	A3-Condition D			X	X	X
Barber pole	A3-Condition E	X			X	X
Camber	A3-Condition F				X	X
Twist	A3-Condition G	X			X	X
Combinations of above	1					X

NOTES:
(1) Two-point (180 deg apart) variable diameter measurement with 180 deg rotation of workpiece. Observe maximum and minimum measured values.
(2) Variable diameter measurement at or near both ends of the workpiece.
(3) Variable diameter measurement scanning the entire length of the workpiece.
(4) Precision rotating spindle or rotating table instrument.
(5) Precision rotating spindle or rotating table instrument with a precision axial slide (cylindricity analyzer).

Table A2 Gage Geometry Effect on Go Ring Gages

Type of Form Error	Figures	Notes
Roundness		
Single flat	A2-Condition A	(1), (4), (6)
Single groove	A2-Condition B	(1), (5), (6)
Ovality or even numbered lobes	A2-Condition C	(1), (4), (5), (6)
Tri-lobe	A2-Condition D	(1), (4), (5), (6)
Odd numbered lobes	A2-Condition D, E	(1), (4), (5), (6)
Irregular lobes	A2-Condition F	(1), (4), (5), (6)
Taper	A3-Condition A	(1), (2), (3), (6)
Straightness		
Barrel shape	A3-Condition B	(1), (2), (6)
Hourglass	A3-Condition C	(1), (2), (3), (4), (6)
Convoluted	A3-Condition D	(1), (4), (6)
Barber pole	A3-Condition E	(1), (4), (6)
Camber	A3-Condition F	(1), (4), (6)
Twist	A3-Condition G	(1), (4), (6)

NOTES:
(1) Smallest effective diameter of gage may exceed the lower tolerance limit of the gage. This increases the probability of fail error and may increase manufacturing cost.
(2) Effective diameter at end of gage may be less than measured size of gage and could be less than lower limit of gage size tolerances. This increases probability of fail error and may increase manufacturing cost.
(3) Effective diameter at end of gage may exceed the measured size of gage and could be above the upper limit of gage size tolerances. Workpiece may appear to be tapered when it is not. User will assume workpiece is wrong. This increases pobability of fail error and may increase manufacturing cost.
(4) Virtual condition of gage may be smaller than the lower tolerance limit of the gage. This increases the probability of fail error and may increase manufacturing cost.
(5) May accept a correspondingly out-of-round workpiece if the form error of the workpiece is aligned with the form error of the gage. This increased probability of pass error can be avoided by rotating the gage while it is engaged with the workpiece.
(6) Form error may reduce gage life because less surface material is available at the gage/workpiece interface and wear rates could increase.

Table A3 Gage Geometry Effect on NoGo Ring Gages

Type of Form Error	Figures	Notes
Roundness		
Single flat	A2-Condition A	(1), (4)
Single groove	A2-Condition B	(5)
Ovality or even numbered lobes	A2-Condition C	(1), (4)
Tri-lobe	A2-Condition D	(1), (4)
Odd numbered lobes	A2-Condition D, E	(1), (4)
Irregular lobes	A2-Condition F	(1), (4)
Taper	A3-Condition A	(1), (2), (3)
Straightness		
Barrel shape	A3-Condition B	(1), (2), (4)
Hourglass	A3-Condition C	(1), (3), (4)
Convoluted	A3-Condition D	(1), (2), (4)
Barber pole	A3-Condition E	(5)
Camber	A3-Condition F	(5)
Twist	A3-Condition G	(5)

NOTES:

(1) Smallest effective diameter of gage may exceed the lower tolerance limit of the gage. This increases the probability of acceptance of product, which is out of its tolerance specification.

(2) Effective diameter at end of gage may be less than measured size of gage and could be less than lower limit of gage size tolerances. This increases probability of acceptance of product, which is out of its tolerance specification.

(3) Effective diameter at end of gage may exceed the measured size of gage and could be above the upper limit of gage size tolerances. Workpiece may appear to be tapered when it is not. User will assume workpiece is wrong. This increases pobability of fail error and may increase manufacturing cost.

(4) Virtual condition of gage may be smaller than the lower tolerance limit of the gage. This increases probability of acceptance of product, which is out of its tolerance specification.

(5) Other conditions of form error that may produce a difference between the actual mating size and the measured size of a NoGo gage are not applicable because the workpiece is not intended to enter the gage.

Table A4 Gage Geometry Effect on Master Ring Gages

Type of Form Error	Figures	Notes
Roundness		
Single flat	A2-Condition A	(1), (3), (4), (5), (7), (8), (11)
Single groove	A2-Condition B	(2), (3), (4), (6), (7), (8)
Ovality or even numbered lobes	A2-Condition C	(1), (2), (3), (4), (5), (6), (7), (8)
Tri-lobe	A2-Condition D	(5), (6), (7)
Odd numbered lobes	A2-Condition D, E	(5), (6), (7)
Irregular lobes	A2-Condition F	(1), (2), (3), (4), (5), (6), (7)
Taper	A3-Condition A	(4), (7)
Straightness		
Barrel shape	A3-Condition B	(4), (5), (6), (7), (9), (10)
Hourglass	A3-Condition C	(4), (5), (7), (9), (10)
Convoluted	A3-Condition D	(4), (5), (6), (7), (9), (10)
Barber pole	A3-Condition E	(3), (4), (5), (6), (7), (9), (10)
Camber	A3-Condition F	(10)
Twist	A3-Condition G	(10)

NOTES:
(1) Diameter across the flat may be less than the measured size of the Master Ring Gage and less than the lower limit of the gage size tolerance.
(2) Diameter across the groove may exceed the measured size of the Master Ring Gage and exceed upper limit of the gage size tolerance.
(3) Gage reading will change abruptly when the Master Ring Gage is rotated across the flat or groove.
(4) Inaccurate gage setting can be avoided by not setting the Master Ring Gage at a localized high or low reading.
(5) Inscribed circle size of the Master Ring Gage may be less than its measured size and could exceed the lower limit of gage size tolerance.
(6) Circumscribed circle size of the Master Ring Gage may be greater than its measured size and could exceed the upper limit of gage size tolerance.
(7) Regularly spaced odd-numbered lobes are not a factor when setting a two-point measuring device. Form error may be apparent when setting a multi-point measuring device (e.g., air spindle).
(8) Gage reading will change from high to low twice with each full rotation of the Master Ring Gage.
(9) Gage reading will change as the Master Ring Gage is moved lengthwise over the measuring device.
(10) Virtual condition of the Master Ring Gage may extend below the measured diameter and could exceed the lower limit of the gage size tolerance. This could cause the gage to be set smaller than intended and workpiece measurements will read larger than the actual size.
(11) Inaccurate gage setting can be avoided by rotating the Master Ring Gage and setting the gage at the highest reading.

Table A5 Typical Causes of Lobing Conditions on Circular Parts

Number of lobes	Causes
2	Inaccuracy in tooling (elliptical). Part not square in machine. Part not square in measuring machine. Uneven lapping process.
3–4	Distortion of part due to clamping in machine or measuring system. Commonly caused by three or four jaw chuck.
3–15	Machining process or grinding process. (Machine bearings, grind wheel condition).
>15	Process and material parameters. Common process parameters include vibration, tool condition, spindle speed, feed rates and medium to high frequency chatter.

NONMANDATORY APPENDIX B
MEASUREMENT UNCERTAINTY

B1 INTRODUCTION

The calculation of the uncertainty in a measurement is an effort to determine a reasonable and standardized level of confidence for the measurement results. There are many techniques for estimating and combining the components of measurement uncertainty. The ISO Report and the NIST Technical Note 1297, are both good documents that offer standardized techniques for performing these calculations. The accepted technique for combining uncertainty sources together is to combine the **standard uncertainty** for each source. This is equivalent to the 1σ estimate of the normalized error source. The standard uncertainty will be used in this appendix.

B2 GENERAL

The uncertainty of measurement is a combination of many different sources of error. Determining this roster of error sources and the magnitudes of the individual components can be difficult, time consuming, and inaccurate without some guidance or experience in this type of process evaluation. This appendix will extend some general guidance and offer examples of uncertainty calculations for plain ring gage measurement.

B3 EXAMPLE

In the appendix example, the uncertainty sources for dimensional measurements will fall into the following categories:

(a) Master gage calibration.

(b) Long term reproducibility of the measurement system.

(c) Thermal uncertainties.

(1) Thermometer calibration.

(2) Coefficient of Thermal Expansion (CTE).

(3) Thermal gradients.

(d) *Elastic Deformation.* probe contact deformation.

(e) *Scale Calibration.* linearity, scale CTE, fit routines.

(f) *Instrument Geometry.* Abbe offset, scale and gage alignment, gage support geometry.

(g) *Artifact.* effects, flatness, roundness, squareness, surface finish, cylindrical form, etc.

For the purpose of this appendix example, the preceding outline of uncertainty sources will be used in the following discussion. We will develop two examples of an uncertainty budget for the comparison of a combination to a plain ring gage using an internal/external comparator. The first case will be for the comparison of a tungsten ring gage to a steel combination. The second case will use the same stack and compare to a steel ring gage. The differences in these uncertainty calculations will be identified and briefly discussed. We will also assume that the combination and the ring gages are the same nominal size.

B4 RELEVANT INPUTS FOR APPENDIX EXAMPLE

Case 1:	Tungsten Carbide Ring Gage
	Diameter = 40 mm
	Thermal Expansion Coefficient = $4.6 \times 10^{-6}/°C \pm 10\%$
Case 2:	Steel Ring Gage
	Diameter = 40 mm
	Thermal Expansion Coefficient = $11.5 \times 10^{-6}/°C \pm 10\%$
Both Cases:	Steel Combination:
	Block 1 = 25 mm ± 0.1 μm
	Block 2 = 15 mm ± 0.1 μm
	Thermal Expansion Coefficient = $11.5 \times 10^{-6}/°C \pm 10\%$
	Room Temperature = (20 ± 1)°C
	Thermometer Uncertainty = ± 0.1°C

Using this information we will now develop the uncertainty budgets according to the outline of uncertainty sources discussed earlier.

B5 MASTER GAGE CALIBRATION

(a) The master gage in this case is the reference master combination. The individual gage blocks are calibrated by a typical commercial laboratory with the total uncertainty on each block of 0.1 micrometer (μm). We will assume this represents the 95% confidence level (2σ). This yields a standard uncertainty, at the 1σ level, of $u = 0.05$ μm, for each gage block in the stack.

(b) The gage blocks are calibrated at their gage points only. Since the blocks are not perfectly flat or parallel and are wrung together, the stack does not generally produce a length exactly the sum of the lengths of the two blocks added together. The added uncertainty for wringing imperfect gage blocks together depends on

the geometry of the blocks. Blocks that are very parallel and flat produce much less uncertainty than those of lesser quality.

A simple test to determine the magnitude of these effects is to wring several stacks of the same length made from two or three blocks. For example, the millimeter stack of (1+9, 2+8, 3+7, 4+6, 5+5) could be made and compared to a 10 mm block. In this example, the grade 1 gage blocks used resulted in an extra variation of 0.030 μm for one wring. For two or more wrings the result is a standard uncertainty of 0.030 μm for each wring.

Our example has only one wring in the combination. However, in typical ring gage comparisons, two end blocks or cover blocks are wrung to the stack, one on each end, to extend the reference length so an internal measurement can be made from the stack. These additional two wrings also add 0.030 μm of uncertainty for each wring. The parallelism of the combination and/or the cover blocks can dramatically affect the size of the resulting internal gap by angling in or flaring out and large systematic errors will be made during transfer. If the cover blocks extend only beyond one side of the combination and form a U-shaped master, the parallelism can not be easily detected. If the cover blocks are large enough to extend past both sides of the combination and form an H-shaped master, the parallelism error can be averaged out of the measurement. Assuming the cover blocks are of high quality, are flat and parallel, and extend beyond the combination on both sides, we can use the average of the measurements from both sides as the reference length. The difference between these lengths can also be used as a process control parameter for checking the quality of the combination and the associated wrings.

These uncertainties associated with the master gage calibration are the same for each case since the same master combination is used in both measurements.

B6 LONG TERM REPRODUCIBILITY OF MECHANICAL COMPARISON

Reproducibility is different from repeatability in the sense that reproducibility is generally associated with long term data where most variables in the measurement process are sampled many times and the combined effects can be quantified without knowledge of the individual components. These effects are very dependent on the type and mechanical condition of the comparator, operator skill, and the number of repetitions of the measurements during the comparison. In addition, reproducibility can be affected by dissimilar geometry between the reference master, in our case a combination and cover block, and the test ring gage. Also critical in ring gage comparisons are the measurement position on the ring bore and the ability to repeat measurements at this same position. The surface finish and taper geometry are important for minimizing these effects on the reproducibility of the process.

One easy method to develop this component for individual laboratories is to maintain a set of check standard ring gages. These gages can be owned by the laboratory and measured on a routine basis using different operators, comparators, and master combinations. The data can be compiled over the long term and the variability of the process can be derived.

From existing reproducibility data available on gage block cylinder calibrations, competent labs making two comparisons of a master and unknown artifacts generally yield a standard uncertainty (1σ) of about 0.040 μm. Ring gages tend to yield slightly higher standard uncertainties on comparable equipment; therefore we will use 0.050 μm as the standard uncertainty for the reproducibility of the measurement comparison for class XX and XXX gages. The uncertainty is the same for each case.

B7 THERMAL UNCERTAINTIES

There are three components of uncertainty related to temperature; the uncertainty in the thermometer calibration, the uncertainty in the thermal expansion of the materials, and the temperature gradients on the apparatus and between the master and test artifacts.

(a) The uncertainty in the thermometer calibration generates an uncertainty in length according to the formula:

$$\Delta L = L\alpha\Delta T$$

where

L = length

ΔT = change in temperature, and

α = CTE

(1) Case 1: We are comparing two gages; one of steel and one of tungsten carbide, and the correction shall be made for both. Therefore the total correction depends on the difference in CTE between the gage and the master generating the following formula.

$$\Delta L = (\alpha_{wc} - \alpha_{teel})\, L\Delta T$$

The length is 40 mm, and the thermometer calibration will be assumed to be as good as the least significant digit, 0.1°C. The uncertainty becomes:

$$\Delta L = (11.5 \times 10^{-6} - 4.6 \times 10^{-6})\,(0.1°\mathrm{C})\,40\ \mathrm{mm} = 0.024\ \mu\mathrm{m}$$

If we assume the uncertainty is from a rectangular distribution, we can divide by $\sqrt{3}$ and get a standard uncertainty of u = 0.012 μm.

(2) Case 2: Since the gages are both of steel, the uncertainty is negligible.

(b) The second source of thermal error is from the uncertainty of the CTE of the artifact material.

(1) Case 1: The gage block standard gives a tolerance on steel gage blocks as 10% of the nominal value supplied by the manufacturer. Experimental measurements on gage blocks confirm this statement. We will assume that the distribution of the expansion coefficients are rectangular with a width of ± 1 ppm/°C for the steel and ± 0.5 ppm/°C for tungsten carbide. This yields a standard uncertainty (1σ level) of ± 0.6 ppm/°C for steel and ± 0.3 ppm/°C for tungsten carbide. If we take the worst case that we are measuring 1°C away from 20°C, we calculate:

$$\Delta L = L(20 - T)\,\Delta\alpha$$

for tungsten carbide:

$$u_{a,wc} = 40 \times 10^{-3}\ \mu\text{m}\ (20 - 21°\text{C})\ 0.3\ \text{ppm}/°\text{C} = 0.012\ \mu\text{m}$$

for steel:

$$u_{a,steel} = 40 \times 10^{-3}\ \mu\text{m}\ (20 - 21°\text{C})\ 0.6\ \text{ppm}/°\text{C} = 0.024\ \mu\text{m}$$

These calculations are only for the standard uncertainty of the correction back to 20 deg. The magnitude of the correction is not calculated here and we assume the correction is applied.

(2) Case 2: Even though both the master and test artifact are steel, the uncertainty of the CTE shall be calculated for each and applied in the budget. We can not assume the CTE for the master and the ring are the same, resulting in a negligible uncertainty. We shall use the value of $u = 0.024\ \mu\text{m}$ for each artifact.

(c) The third source of thermal uncertainty is for the unknown temperature gradients that exist between the master stack and the test ring. We can not assume that simply because the master and test artifacts are close together, that they are the same temperature. Testing has shown that even for environmentally well-controlled laboratories the gradients on comparator anvils can be as much as 0.05°C only inches apart. Furthermore, to accurately characterize these gradients, a high-resolution thermometer is required. If we use a thermometer with a least significant digit of 0.1°C, the gradients can not be known better than the resolution. Using this best case of a span of ± 0.1°C and assuming a rectangular distribution, we get a standard uncertainty in the thermal gradient of ± 0.057°C. This error applies to the full length of the gage and using steel in the calculation, we get:

$$u_{gradient} = 40 \times 10^{-3}\ \mu\text{m}\ (0.057°\text{C})\ 11.5\ \text{ppm}/°\text{C} = 0.026\ \mu\text{m}$$

This error would be the same for both cases since steel is present in each comparison.

B8 ELASTIC DEFORMATION

The elastic deformation that occurs during the measurement is calculated from Puttock and Thwaite CSIRO Technical Paper No. 25. If the contact geometry is well known, the main source of uncertainty is from the elastic modulus of the materials involved in the measurements. We will assume that these values are good to 5%; the variation we find between a number of standard references for common material properties.

In our measurements there are two deformation conditions. They are:

(a) A sphere in contact with a plane – the comparator contacts to the combination.

(b) A sphere in contact with an internal cylinder – the comparator contacts to the ring gage.

(1) Case 1: The correction required for the steel combination is 0.53 μm. The correction require for the tungsten carbide ring gage is 0.32 μm. Since the block stack and the ring gage are different materials and the calculated corrections are not the same, each variable in the calculation is now important and shall be verified for accuracy. Since the elastic constant values are known no better than 5%, the applied force and the comparator probe radius should also be known to this level to minimize the uncertainty of the correction. Of most importance is the comparator probe radius. These probes, regardless of their material, are known to wear down quickly during routine use resulting in deformation corrections that can be incorrect by more than 50%. Large systematic errors will result if this condition is not identified.

For the purposes here, it is assumed the applied force and the probe geometry have been measured and are known to better than 5%. The resulting standard uncertainty would be 0.015 μm.

(2) Case 2: The correction required for the deformation of the steel combination is 0.53 μm. The correction required for the deformation of the steel ring gage is 0.52 μm. Since the block stack and the ring are both steel, the calculated corrections are nearly the same. This also makes the accuracy of the correction almost independent from the other variables in the calculations, namely the probe geometry and the applied force of the contacts. From the elastic constant uncertainty we assume the distribution is rectangular with a range of ± 5%. The result is a standard uncertainty of $u = 0.015\ \mu\text{m}$.

For our purposes here, we will assume the applied force and the probe geometry has been measured and is known to better than 5%. The resulting standard uncertainty would be the same as in the first case, $u = 0.015\ \mu\text{m}$.

B9 SCALE CALIBRATION

The ring comparator scale should be calibrated using two or more calibrated gage blocks. If the uncertainty of each block were 0.1 μm, and the comparator scale 2.5 μm, the uncertainty in the slope, at the 1σ level, would be about 4%. The difference between the master combination and the test ring gage is always less than 1μm, leading to a standard uncertainty of 4% of 1 μm, or 0.040 μm. This would be the same for both Case 1 and Case 2.

B10 INSTRUMENT GEOMETRY

The master stack and the ring gage are manipulated to assure that the alignment errors are not significant. The ring gage is moved until the maximum diameter is recorded while the master stack is rotated until the minimum value is observed. Since both errors are cosine errors this can be done with little difficulty.

One potential source of error is the alignment of the contacts. If the relative motion of the two contacts is parallel but not coincident, the transfer of length from the combination to the ring gage will result in an error. This effect is difficult to identify since most ring comparators have a very small range of motion, less than 5 μm. This effect is larger for small diameter rings or for rings where the contact probe diameters are close in size to the diameter of the ring being measured. For the 40 mm ring in this example, the effect is negligible.

B11 ARTIFACT GEOMETRY

Artifact geometry effects can be some of the largest sources of uncertainty in the measurement of ring gages. These effects can vary depending on a variety of factors including the squareness and roundness of the ring, the taper and form of the ring bore at or near the measurement positions, and the ability to reposition the ring consistently during the measurement. It is common to have some artifact geometry effects included in the reproducibility term since the ability to re-position the ring during measurement will sample some artifact geometry as well as the other unknowns in the process.

For XXX or XX gages, the effects of squareness and roundness are small for the measurement of specific, well-marked diameters. The taper or cylindrical form of the bore can be much more variable. Variations of as much as 0.05 μm are commonly seen within increments of as little as 1 mm throughout the length of the bore. With positioning accuracy of no better than 0.5 mm, we will use an estimated value for the standard uncertainty of 0.025 μm for these artifact's effects.

Table B1 Summary of Uncertainties

Source of Uncertainty	Case 1 u [μm] (μin.)	Case 2 u [μm] (μin.)
Master block 1 calibration	0.050 (2.0)	0.050 (2.0)
Master block 2 calibration	0.050 (2.0)	0.050 (2.0)
Wring between master blocks	0.030 (1.3)	0.030 (1.3)
Wring of 1st cover block	0.030 (1.3)	0.030 (1.3)
Wring of 2nd cover block	0.030 (1.3)	0.030 (1.3)
Reproducibility	0.050 (2.0)	0.050 (2.0)
Thermometer calibration	0.012 (0.5)	negligible
CTE of block stack	0.024 (1.0)	0.024 (1.0)
CTE of ring gage	0.012 (0.5)	0.024 (1.0)
Thermal gradients	0.026 (1.0)	0.026 (1.0)
Elastic deformation	0.015 (0.4)	0.015 (0.4)
Scale calibration	0.040 (1.6)	0.040 (1.6)
Instrument geometry	negligible	negligible
Artifact geometry	0.025 (1.0)	0.025 (1.0)
TOTAL (RSS)	0.119 (4.7)	0.120 (4.7)
TOTAL (K = 2)	0.238 (9.4)	0.239 (9.4)

Table B1 is a summary of the calculated uncertainties with each variable listed, including the totaled result.

The total expanded uncertainty, using a coverage factor of $k = 2$ (95% confidence level) is ±0.24 μm (±9.4 μin.) in each case. For measurement processes with uncertainties at these levels, the comparison of dissimilar materials does not appreciably increase the uncertainty if the deformation corrections can be made accurately. This was the important assumption made in this example.

From an analysis of the uncertainty budget, there are several sources of error that have similar magnitudes. To lower the uncertainty of this measurement, the largest sources of error shall be addressed first. Notice that the first five error sources are related to the master combination. All of these can be reduced to one line if a master ring gage would be used in the comparison. Depending on the source of the master ring calibration, the uncertainty of this ring could be substantially less than the total of the combination uncertainties. The errors associated with the CTE of the materials can be reduced to negligible levels if the comparison is done very close to 20°C. The uncertainty in the scale calibration can also be reduced if the master and test ring can be very close in size.

NONMANDATORY APPENDIX C
ISO CYLINDRICAL RING BLANK DESIGN
[Section 5.1, Excerpt from ISO 3670-1979 (E)]

C1 RING GAUGES

C1.1 Plain Ring Gauges

The blanks shall be made of good quality steel and may be supplied in the soft or hard condition. Hardened blanks, more particularly those of the larger sizes, should be stabilized before they are completed.

NOTE: When blanks are required hardened throughout, this should be specified by the purchaser.

The blanks shall be machined to the general dimensions specified in Table C1 with a finishing allowance where necessary. The amount of excess material left to allow for finishing to size is at the discretion of the gauge manufacturer.

The blanks, the general dimensions of which are specified in Table C1, are intended for general purpose gauges and for master gauges used as standards for reference purposes or for the setting of measuring instruments.

Two thicknesses are shown for each diameter range, the choice of thickness depending upon the application of the gauge. For example, in some circumstances it may be necessary to adhere strictly to the Taylor principle and use a GO ring gauge of a thickness equal to the length to be checked.

It is customary for a NOT GO gauge to be identified by means of a circular groove as shown in Fig. C2.

Table C1 General Dimensions for Plain Ring Gauge Blanks

Nominal Diameter, d		Dimensions in Millimetres			
above	Up to (incl.)	External Diameter D	Thickness, L_1	Thickness L_2	(NOT GO only), b
1 [Note (1)]	2,5	16	4	6	1
2,5	5	22	5	10	1
5	10	32	8	12	1
10	15	38	10	14	2
15	20	45	12	16	2
20	25	53	14	18	2
25	32	63	16	20	2
32	40	71	18	24	2
40	50	85	20	32	3
50	60	100	20	32	3
60	70	112	24	32	3
70	80	125	24	32	3
80	90	140	24	32	3
90	100	160	24	32	3

NOTE:
(1) Included.

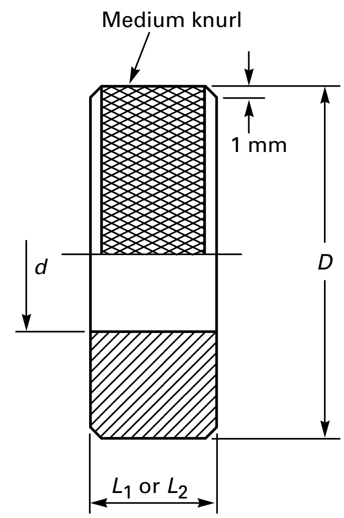


Fig. C1 Go Gauge

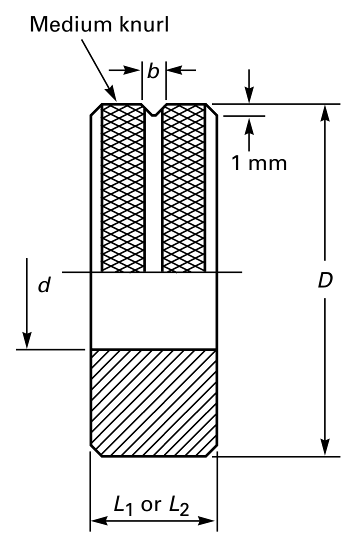


Fig. C2 Identification for Not Go Gauge

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ISBN 0-7918-2761-5

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