ASME Y14.5.1-2019
[Revision of ASME Y14.5.1M-1994 (R2012)]

Mathematical Definition of Dimensioning and Tolerancing Principles

Engineering Product Definition and Related Documentation Practices

AN INTERNATIONAL STANDARD

The American Society of Mechanical Engineers

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AN INTERNATIONAL STANDARD

The American Society of Mechanical Engineers
Two Park Avenue • New York, NY • 10016 USA

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

CONTENTS

Tables

FOREWORD

This edition is a revision of ASME Y14.5.1M-1994, Mathematical Definition of Dimensioning and Tolerancing Principles, supporting Y14.5-2009. Efforts focused on improving usability with Y14.5 have resulted in harmonization of terms where possible and a realignment of sections consistent with Y14.5-2009. This revision also addresses proposals submitted by the public or members of the Y14 Standards Committee and affiliated subcommittees. See Nonmandatory Appendix A, Principle Changes and Improvements.

Work on this revision began in May of 2012 followed by semiannual face-to-face meetings and numerous online collaborative meetings to refine content and disposition comments. Comments on key areas are provided below to add some context to these revisions.

This revision includes a new stabilization definition for irregularities on datum features specified at RMB, which provides an alternative to the candidate datum set. SC5 had moved toward the concept of a single-stable solution that minimizes the separation between the datum feature and the true geometric counterpart, and SC5.1 was asked to study the concept and recommend a mathematical definition. A stable Constrained L2 datum definition was selected, which applies as an alternate stabilization definition for Y14.5-2009 and the default stabilization definition for Y14.5-2018. See Nonmandatory Appendix B for results of the study and mathematical definitions.

Profile tolerancing was a major focus of development work and the section was completely rewritten. The actual value of profile was changed from the deviation-based two-value definition to a zone-based single-value definition compatible with Y14.5's tolerance zone definitions. This provides a consistent treatment of unequally disposed and unilateral profile zones, with no change in conformance results. The updated definition allows direct comparison of the actual value with the specified tolerance value, and consistency with actual value definitions for other geometric tolerances.

Redevelopment of the profile section also created the requirement to address applications with multiple features and a variety of degree of freedom constraints. This was accomplished by treating profile tolerances as systems with degrees of freedom and constraints, with the Y14.5 tolerance zone and datum reference frame definitions providing the initial conditions. Actual values are defined for a wide variety of profile applications including single features, multifeature groups with and without datum features, simultaneous requirements, and composite profile tolerances.

The mathematical definitions for size have not changed; they continue to use the sweeping ball concept to define the tolerance zone volume. Two nonmandatory definitions for local size have been added: one based on opposed points and the other based on inscribed/circumscribed circular elements.

Text and figure edits were made to improve readability and clarify content. Changes in sentence structure, organization of content, and method of illustration are not an indication of technical changes.

This Standard is available for public review on a continuing basis. This provides an opportunity for additional public review input from industry, academia, regulatory agencies, and the public-at-large.

ASME Y14.5.1-2019 was approved by ANSI as an American National Standard on November 7, 2019.

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Proposing 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.

This Standard is always open for comment, and the Committee welcomes proposals for revisions. 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.

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Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

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Section 1
Scope and Definitions

1.1 SCOPE

This Standard presents a mathematical definition of geometrical dimensioning and tolerancing consistent with the principles and practices of ASME Y14.5-2009, enabling determination of actual values. While the general format of this Standard parallels that of ASME Y14.5-2009, the latter document should be consulted for practices relating to dimensioning and tolerancing for use on engineering product definition and in related documentation.

Textual references are included throughout this Standard which are direct quotations from ASME Y14.5-2009. All such quotations are identified by italicized type and include paragraph reference within square brackets. Any direct references to other documents are identified by an immediate citation.

This Standard applies to product definition in any representation. When reference is made in this Standard to an engineering product definition, it applies to any form of product specification.

1.1.1 Reference to Gaging

This Standard is not intended as a gaging standard. Any reference to gaging is included for explanatory purposes only.

1.2 ASME Y14 SERIES CONVENTIONS

The conventions in paras. 1.2.1 through 1.2.9 are used in this and other ASME Y14 standards.

1.2.1 Mandatory, Recommended, Guidance, and Optional Words

(a) The word "shall" establishes a requirement.

(b) The word "will" establishes a declaration of purpose on the part of the design activity.

(c) The word "should" establishes a recommended practice.

(d) The word "may" establishes an allowed practice.

(e) The words "typical," "example," "for reference," and the Latin abbreviation "e.g." indicate suggestions given for guidance only.

(f) The word "or" used in conjunction with a requirement or a recommended practice indicates that there are two or more options for complying with the stated requirement or practice.

(g) The phrase "unless otherwise specified" or "UOS" shall be used to indicate a default requirement. The phrase is used when the default is a generally applied requirement and an exception may be provided by another document or requirement.

1.2.2 Cross-Reference of Standards

Cross-reference of standards in text with or without a date following the standard designator shall be interpreted as follows:

(a) Reference to other ASME Y14 standards in the text without a date following the standard designator indicates that the edition of the standard identified in the References section (subsection 1.3) shall be used to meet the requirement.

(b) Reference to other ASME Y14 standards in the text with a date following the standard designator indicates that only that edition of the standard shall be used to meet the requirement.

1.2.3 Invocation of Referenced Standards

The following examples define the invocation of a standard when specified in the References section (subsection 1.3) and referenced in the text of this Standard:

(a) When a referenced standard is cited in the text with no limitations to a specific subject or paragraph(s) of the standard, the entire standard is invoked. For example, "Dimensioning and tolerancing shall be in accordance with ASME Y14.5" is invoking the complete standard because the subject of the standard is dimensioning and tolerancing and no specific subject or paragraph(s) within the standard are invoked.

(b) When a referenced standard is cited in the text with limitations to a specific subject or paragraph(s) of the standard, only the paragraph(s) on that subject is invoked. For example, "Assign part or identifying numbers in accordance with ASME Y14.100" is invoking only the paragraph(s) on part or identifying numbers because the subject of the standard is engineering drawing practices and part or identifying numbers is a specific subject within the standard.

(c) When a referenced standard is cited in the text without an invoking statement such as "in accordance with," the standard is invoked for guidance only. For example, "For gaging principles, see ASME Y14.43" is

only for guidance and no portion of the standard is invoked.

1.2.4 Parentheses Following a Definition

When a definition is followed by a standard referenced in parentheses, the standard referenced in parentheses is the source for the definition.

1.2.5 Notes

Notes depicted in this Standard in ALL UPPERCASE letters are intended to reflect actual drawing entries. Notes depicted in initial uppercase or lowercase letters are to be considered supporting data to the contents of this Standard and are not intended for literal entry on drawings. A statement requiring the addition of a note with the qualifier "such as" is a requirement to add a note, and the content of the note is allowed to vary to suit the application.

1.2.6 Acronyms and Abbreviations

Acronyms and abbreviations are spelled out the first time used in this Standard, followed by the acronym or abbreviation in parentheses. The acronym is used thereafter throughout the text.

1.2.7 Units

The International System of Units (SI) is featured in this Standard. It should be understood that U.S. Customary units could equally have been used without prejudice to the principles established.

1.2.8 Figures

The figures in this Standard are intended only as illustrations to aid the user in understanding the practices described in the text. In some cases, figures show a level of detail as needed for emphasis. In other cases, figures are incomplete by intent so as to illustrate a concept or facet thereof. The absence of figure(s) has no bearing on the applicability of the stated requirements or practice. To comply with the requirements of this Standard, actual data sets shall meet the content requirements set forth in the text. To assist the user of this Standard, the designated paragraph(s) in which an illustration is referenced appears in the lower right-hand corner of each figure. This reference may not be all-inclusive. The absence of a paragraph reference is not a reason to assume inapplicability. Some figures are illustrations of models in a three-dimensional environment. The absence of dimensioning and tolerancing annotations in a view may indicate that the product definition is defined in 3D. Dimensions that locate or orient and are not shown are considered basic and shall be queried to determine the intended requirement. When the letter "h" is used in figures for letter heights or for symbol proportions, select the applicable letter height in accordance with ASME Y14.2. Multiview drawings contained within figures are third-angle projection.

1.2.9 Precedence of Standards

The following are ASME Y14 standards that are basic engineering drawing standards:

ASME Y14.1, Decimal Inch Drawing Sheet Size and Format
ASME Y14.1M, Metric Drawing Sheet Size and Format
ASME Y14.2, Line Conventions and Lettering
ASME Y14.3, Orthographic and Pictorial Views
ASME Y14.5, Dimensioning and Tolerancing
ASME Y14.24, Types and Applications of Engineering Drawings
ASME Y14.34, Associated Lists
ASME Y14.35, Revision of Engineering Drawings and Associated Documents
ASME Y14.36, Surface Texture Symbols
ASME Y14.38, Abbreviations and Acronyms for Use on Drawings and Related Documents
ASME Y14.41, Digital Product Definition Data Practices
ASME Y14.100, Engineering Drawing Practices

All other ASME Y14 standards are considered specialty types of standards and contain additional requirements or make exceptions to the basic standards as required to support a process or type of drawing.

1.3 REFERENCES

The following revisions of American National Standards form a part of this Standard to the extent specified herein. A more recent revision may be used provided there is no conflict with the text of this Standard. In the event of a conflict between the text of this Standard and the references cited herein, the text of this Standard shall take precedence.

ASME Y14.5-2009, Dimensioning and Tolerancing
ASME Y14.41-2012, Digital Product Definition Data Practices
Publisher: The American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990 (www.asme.org)

1.4 MATHEMATICAL NOTATION

This subsection describes the mathematical notation used throughout this Standard, including symbology (typographic conventions) and algebraic notation.

1.4.1 Symbology

All mathematical equations in this Standard are relationships between real numbers, three-dimensional vectors, coordinate systems associated with datum reference frames, and sets of these quantities. The symbol conventions shown in Table 1-1 are used for these quantities.

These symbols may be subscripted to distinguish between distinct quantities. Such subscripts do not change the nature of the designated quantity.

Technically, there is a difference between a vector and a vector with location. Generally in this Standard, vectors do not have location. In particular, direction vectors, which are often defined for specific points on curves or surfaces, are functions of location on the geometry, but are not located at those points. (Another conventional view is that all vectors are located at the origin.) Throughout this Standard, vectors are used to denote points in space. While there is a technical difference between a vector and a point in space, the equivalence used in this Standard should not cause confusion.

1.4.2 Algebraic Notation

A vector can be expanded into scalar components. Let $\hat{\boldsymbol{\imath}}$, $\hat{\boldsymbol{\jmath}}$, and $\hat{\boldsymbol{k}}$ be the unit vectors along the x, y, and z axes, respectively, of a coordinate system. Then a vector $\vec{\boldsymbol{V}}$ can be uniquely expanded as

$$\vec{\boldsymbol{V}} = a\,\hat{\boldsymbol{\imath}} + b\,\hat{\boldsymbol{\jmath}} + c\,\hat{\boldsymbol{k}}$$

The vector can be written $\vec{\boldsymbol{V}} = (a, b, c)$. The magnitude (length) of vector $\vec{\boldsymbol{V}}$ is denoted by $|\vec{\boldsymbol{V}}|$ and can be evaluated by

$$\left|\vec{\boldsymbol{V}}\right| = \sqrt{a^2 + b^2 + c^2}$$

A unit vector $\vec{\boldsymbol{V}}$ is any vector with magnitude equal to one. The scalar product (dot product; inner product) of two vectors $\vec{\boldsymbol{V}}_1 = (a_1, b_1, c_1)$ and $\vec{\boldsymbol{V}}_2 = (a_2, b_2, c_2)$ is denoted by $\vec{\boldsymbol{V}}_1 \cdot \vec{\boldsymbol{V}}_2$. The scalar product is a real number given by

$$\vec{\boldsymbol{V}}_1 \cdot \vec{\boldsymbol{V}}_2 = a_1a_2 + b_1b_2 + c_1c_2$$

and is equal in value to the product of the lengths of the two vectors times the cosine of the angle between them. The cross product (vector product) of two vectors $\vec{\boldsymbol{V}}_1$ and $\vec{\boldsymbol{V}}_2$ is denoted by $\vec{\boldsymbol{V}}_1 \times \vec{\boldsymbol{V}}_2$. The cross product is a vector $\vec{\boldsymbol{V}}_3 = (a_3, b_3, c_3)$with components given by

$$\begin{aligned} a_3 &= b_1c_2 - b_2c_1 \\ b_3 &= a_2c_1 - a_1c_2 \\ c_3 &= a_1b_2 - a_2b_1 \end{aligned}$$

The magnitude of the cross product is equal in value to the product of the lengths of the two vectors times the sine of the angle between them.

For a given feature, the notation $r(\vec{\boldsymbol{P}}, \Gamma)$ will denote the distance from a point $\vec{\boldsymbol{P}}$ to true position (see para. 1.4.1) in datum reference frame Γ. When the datum reference frame is understood from the context, the notation $r(\vec{\boldsymbol{P}})$ will be used. Figure 1-1 shows a case of a true position axis. If the axis is represented by a point $\vec{\boldsymbol{P}}_0$ on the axis and a unit vector $\widehat{\boldsymbol{N}}$, then $r(\vec{\boldsymbol{P}})$ can be evaluated by either of the following formulas:

$$r(\vec{\boldsymbol{P}}) = \sqrt{\left|\vec{\boldsymbol{P}} - \vec{\boldsymbol{P}}_0\right|^2 - \left[\left(\vec{\boldsymbol{P}} - \vec{\boldsymbol{P}}_0\right)\cdot\widehat{\boldsymbol{N}}\right]^2}$$

or

$$r(\vec{\boldsymbol{P}}) = \left|\left(\vec{\boldsymbol{P}} - \vec{\boldsymbol{P}}_0\right) \times \widehat{\boldsymbol{N}}\right|$$

The first equation is a version of the Pythagorean Theorem. The second equation is based on the properties of the cross product. See Figure 1-1.

1.5 DEFINITIONS

The following terms are defined as their use applies to this Standard. ASME Y14.5-2009 should be consulted for definitions applying to dimensioning and tolerancing.

1.5.1 Actual Value

actual value: a unique numerical value representing a geometric characteristic associated with one or more actual features.

NOTE: Example characteristics are flatness, perpendicularity, position, actual mating envelope size, and actual local size. Later Sections of this Standard provide rules for the determination of actual values for specific characteristics.

1.5.2 Candidate Datum

candidate datum: one of possibly multiple datums that may be established from a datum feature (see subsection 4.7).

1.5.3 Candidate Datum Reference Frame

candidate datum reference frame: one of possibly multiple datum reference frames that may be established from one or more datum features.

1.5.4 Candidate Datum Reference Frame Set

candidate datum reference frame set: the set of all candidate datum reference frames established from a set of referenced datums.

1.5.5 Candidate Datum Set

candidate datum set: the set of all candidate datums that can be established from a datum feature. See subsection 4.7.

1.5.6 Conformance to a Geometric Tolerance

conformance to a geometric tolerance: applied to a feature, that condition in which the feature does not violate the requirements defined by the specified tolerance.

1.5.7 Cutting Surface

cutting surface: a theoretical surface that, when intersected with a feature, results in a line element.

EXAMPLE: A conical cutting surface coaxial with a datum axis could be used in circular runout evaluation for a surface nominally at an angle to the datum axis, as shown in Figure 1-2. The intersection results in a circular line element that is evaluated.

NOTES:
(1) A cutting plane is a cutting surface.
(2) The tolerance zone is a subset of the cutting surface.

1.5.8 Derived Median Line

derived median line: see ASME Y14.5-2009 [1.3.31].

1.5.9 Derived Median Plane

derived median plane: see ASME Y14.5-2009 [1.3.30].

1.5.10 Design Geometry

design geometry: geometry explicitly represented in the technical product definition (e.g., drawing or CAD model). This geometry is a representation from which tolerance zones can be constructed.

NOTE: The design geometry is not required to be at the center of the tolerance zone (e.g., the case of unequally disposed profile tolerances).

1.5.11 Direction Vector

direction vector: a unit vector. Conventionally, directions are associated with various geometries as follows. The direction vector of a straight line (or pair of parallel lines) is parallel to the line(s). The direction vector of a plane (or a pair of parallel planes) is normal to the plane. The direction vector of a cylinder is the direction vector of the cylinder axis.

1.5.12 Element, Circular

element, circular: a circular element is a closed line element that is nominally a circle.

Examples of cutting surfaces that can create circular elements are

(a) a cone with axis coincident with the datum axis for circular runout

(b) a plane perpendicular to a spine for circularity

1.5.13 Element, Line

element, line: a line (either closed or open, straight or curved), e.g., a one-dimensional manifold, resulting from the intersection of a feature and a specified cutting surface.

1.5.14 Engineering Data

engineering data: engineering documents such as drawings, associated lists, accompanying documents, specifications, standards, or other information prepared or used by a design activity and relating to the design, manufacture, procurement, testing, or inspection of items (see ASME Y14.100-2017).

1.5.15 Envelope, Actual Mating

envelope, actual mating: see ASME Y14.5-2009 [1.3.25].

1.5.16 Envelope, Actual Minimum Material

envelope, actual minimum material: see ASME Y14.5-2009 [1.3.26].

1.5.17 Feature

Per ASME Y14.5-2009

feature: a physical portion of a part such as a surface, pin hole, or slot or its representation on drawings, models, or digital data files. [1.3.27]

NOTE: For the purposes of this Standard, a feature is an identifiable subset (or finite collection of subsets) of the surface of a part. A nominal feature is a subset of the nominal surface, while an actual feature is a subset of the actual surface.

A feature is required to be a two-dimensional surface, that is, a two-dimensional manifold, possibly with boundary (see Nonmandatory Appendix E, section E-2).

1.5.18 Feature of Size, External

feature of size, external: a feature of size where each surface normal is directed away from the feature's resolved geometry.

NOTE: Surface normals point away from the material.

1.5.19 Feature of Size, Internal

feature of size, internal: a feature of size where each surface normal is directed toward the feature's resolved geometry.

NOTE: Surface normals point away from the material.

1.5.20 Half-Space

half-space: one of two regions separated by a theoretical surface that partitions space into exactly two regions. These regions can be finite (e.g., the interior of a spherical surface) or infinite (e.g., the region on either side of a planar surface).

NOTES:
(1) Half-spaces are used to define tolerance zones.
(2) The two half-spaces are complements of one another.

1.5.21 Perfect Form

perfect form: a geometric shape that corresponds to the design geometry except for allowable variations in size, location, or orientation.

1.5.22 Resolved Geometry

resolved geometry: the resolved geometry of a regular feature of size is the center point of a sphere, the axis of a cylinder, or the center plane of a width.

1.5.23 Size, Actual Mating

size, actual mating: a numerical value corresponding to the actual mating envelope. This value may be a diameter for a spherical or cylindrical envelope, or width for a parallel-plane envelope, depending on the context. The radius of a cylindrical or spherical actual mating envelope will be designated r_{AM}.

1.5.24 Size, Actual Minimum Material

size, actual minimum material: a numerical value corresponding to the actual minimum material envelope. This value may be a diameter for a spherical or cylindrical envelope, or width for a parallel-plane envelope, depending on the context. The radius of a cylindrical or spherical actual minimum material envelope will be designated r_{AMM}.

1.5.25 Spine

spine: a point, simple (non-self-intersecting) curve, or simple surface. Spines are used in the definitions of size and circularity.

NOTE: Some applications of spines require them to be tangent-continuous; see Nonmandatory Appendix E, section E-3.

1.5.26 Spine, Local Size

spine, local size: a tangent-continuous spine from which cross sections are determined for actual local size determination.

1.5.27 Surface of Support

surface of support: a theoretical surface that contacts an actual feature at one or more points, such that the feature is not on both sides of the surface. See Figure 1-3.

1.5.28 Tolerance Zone

tolerance zone: a zone whose descriptive parameter t corresponds to the specified tolerance value t_0. Conformance is determined by containment of the relevant actual part geometry (either surface or derived) within the tolerance zone.

NOTE: The difference between tolerance zones and other zones is that tolerance zones are inferred from the product specification.

1.5.29 True Position

Per ASME Y14.5-2009

true position: the theoretically exact location of a feature of size, as established by basic dimensions. [1.3.64]

NOTE: Irregular features of size type b, when specified with a profile tolerance, do not have true position.

1.5.30 True Profile

Per ASME Y14.5-2009

true profile: a profile defined by basic radii, basic angular dimensions, basic coordinate dimensions, basic size dimensions, undimensioned drawings, formulas, or mathematical data, including design models. [8.2]

NOTE: The true profile is a subset of the design geometry.

1.6 SUMMARY OF CONVENTIONAL DESIGNATIONS

Throughout this Standard, conventional designations are used for various quantities. This subsection summarizes these conventions.

$\hat{C}_P$ = direction vector of a cutting plane
$\hat{\boldsymbol{D}}_1$ = direction vector of the primary datum plane
$\hat{\boldsymbol{D}}_2$ = direction vector of the secondary datum plane
$\hat{\boldsymbol{D}}_3$ = direction vector of the tertiary datum plane
$\hat{\boldsymbol{N}}$ = direction vector of the surface normal
$\vec{\boldsymbol{P}}$ = position vector
$r(\vec{\boldsymbol{P}}, \Gamma)$ = the distance of a point $\vec{\boldsymbol{P}}$ to true position in datum reference frame Γ
$r(\vec{\boldsymbol{P}})$ = the distance of a point $\vec{\boldsymbol{P}}$ to true position, in the case that the datum reference frame is understood from context
r_{AM} = actual mating size (radius)
r_{AMM} = actual minimum material size (radius)
r_{TP} = true position mating size (radius)
r_{TPMM} = true position minimum material size (radius)
$\hat{\boldsymbol{T}}$ = direction vector of a zone
t = a value or size of a zone
t_0 = a specific tolerance disclosed in an engineering product definition or part specification
Γ = a candidate datum reference frame

1.7 FORMAT

The format used in this Standard for explanation of geometric characteristics is as follows:

Table 1-1 Mathematical Symbology

Quantity	Symbol	Presentation
Real numbers	t, r, and θ	Plain-face, italic, lowercase English or lowercase Greek letters
Vectors	$\vec{\boldsymbol{T}}$	Boldface, italic English letters with an arrow diacritical mark
Unit vectors	$\hat{\boldsymbol{N}}$	Boldface, italic English letters with a caret diacritical mark
Functions (real or vector-valued)	$r(\vec{\boldsymbol{P}})$	A real number or vector symbol (depending on the kind of value of the function) followed by the parameters of the function in parentheses
Datum reference frames (coordinate systems)	Γ	Plain-face, uppercase Greek letter
Sets	S, F	Plain-face, italic, uppercase English letters

(a) Definition — narrative and mathematical description of the tolerance zone

(b) Conformance — mathematical definition of the conformance

(c) Actual value — mathematical definition of actual value

NOTE: Definitions of conformance and actual values may contain both narrative and mathematical descriptions; in all cases the mathematics shall have precedence.

Figure 1-1 Example: Distance From a Point to a True Position Axis

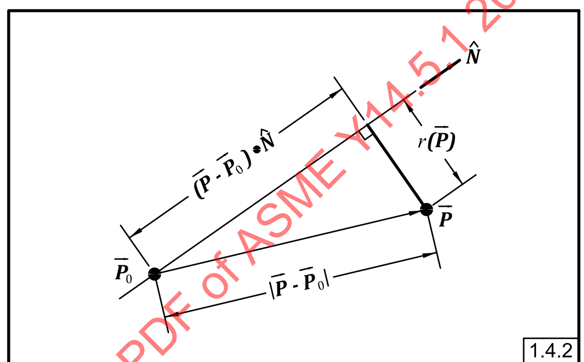


Figure 1-2 Example: Cutting Surfaces to Evaluate Circular Runout

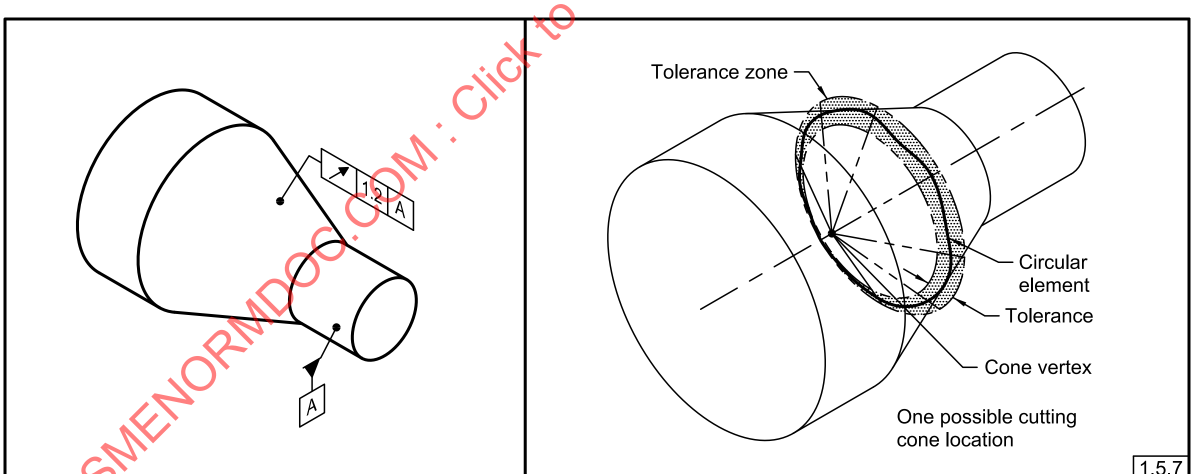
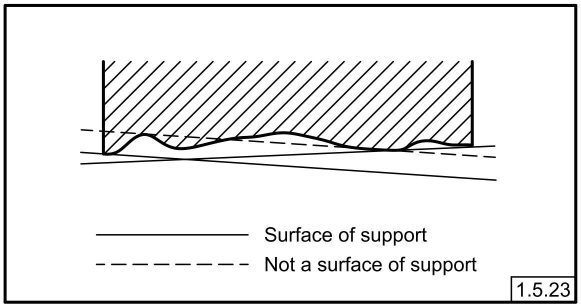


Figure 1-3 Examples of a Planar Surface of Support



Section 2
General Tolerancing and Related Principles

2.1 SURFACE POINTS

This Standard describes the relationship between points on the surface of a part and mathematically defined tolerance zones. In order to effectively apply mathematics to these relationships, it is assumed that the location of the points on the surface are known exactly and it is also known to which feature each point belongs.

NOTES:
(1) The definition of what constitutes an "actual surface," whether on an atomic scale or some other scale, is not addressed in this Standard. What constitutes an "actual surface" may vary by industry and application.
(2) The assignment of points to specific features is known as partitioning. This process is not addressed in this Standard.

2.2 DIMENSION ORIGIN

When a dimension origin symbol is used to specify the distance between two features, the feature from which the dimension originates defines an origin plane for defining the tolerance zone. In such cases, the origin plane shall be established using the same rules as are provided for primary datum features (although a datum is not created). See Section 4, Datum Reference Frames.

2.3 FEATURES OF SIZE

Features of size are classified as regular, irregular (type a), or irregular (type b). These are abbreviated FOS, IFOSa, or IFOSb for ease of notation. Per ASME Y14.5-2009

Regular feature of size: one cylindrical or spherical surface, a circular element, and a set of two opposed parallel elements or opposed parallel surfaces, each of which is associated with a directly toleranced dimension. [1.3.32.2]

Circular elements and opposed parallel elements can be considered [regular] "elements of size" when defined with appropriate cutting surface (see para. 1.5.7).

Per ASME Y14.5-2009, an IFOSa is "*a directly toleranced feature or collection of features that may contain or be contained by an actual mating envelope that is a sphere, cylinder, or pair of parallel planes.*" [1.3.32.2(a)] See Figure 2-1.

NOTE: For an IFOSa, the actual mating envelope is explicitly defined by the Engineering Data. For example, supplemental geometry defining a cylinder or parallel planes is needed to identify the feature of size in Figure 2-1.

Per ASME Y14.5-2009, an IFOSb is "*a directly toleranced feature or collection of features that may contain or be contained by an actual mating envelope other than a sphere, cylinder, or pair of parallel planes.*" [1.3.32.2(b)] See Figure 2-6.

This subsection establishes definitions for the size limits, conformance, and actual size value for features of size. Subject to Rule #1 of ASME Y14.5-2009 [2.7.1], size limits of regular features of size also control form variation. The method by which Rule #1 is applied is discussed in para. 2.3.2.1. For the definition of form controls, refer to Section 5.

2.3.1 Limits of Size

Size is the value used to characterize a feature of size. A size tolerance describes both upper and lower limits for this parameter. A feature of size satisfies its size tolerance if the feature is contained within a tolerance zone corresponding to these limits. Paragraphs 2.3.1 through 2.3.4 are applicable for regular features of size and IFOSa; para. 2.3.5 applies to IFOSb.

(a) Definition. A size tolerance zone is the volume between two half-space boundaries, to be described below. The tolerance zone does not have a unique form. Each half-space boundary is formed by sweeping a ball of appropriate radius along an acceptable spine, as discussed below. The radii of the balls are determined by the size limits: one ball radius is the least material condition limit (r_{LMC}) and one is the maximum material condition limit (r_{MMC}).

A zero-dimensional spine is a point, and applies to spherical features. A one-dimensional spine is a simple (non-self-intersecting) curve in space, and applies to cylindrical features. A two-dimensional spine is a simple (non-self-intersecting) surface, and applies to parallel-plane features. These three types of spines can be more rigorously defined, respectively, as connected regular (in the relative topology) subsets of d-manifolds, for $d = 0, 1$, and 2. A d-dimensional spine will be denoted as S^d. Also, a (solid) ball of radius r will be denoted as B_r.

A solid $G(S^d, B_r)$ is obtained by sweeping the ball B_r so that its center lies in S^d. $G(S^0, B_r)$ is a single ball bounded by a sphere. If S^1 is a line segment, $G(S^1, B_r)$ is a solid bounded by a cylindrical surface and two spherical end caps. If S^2 is a planar patch, $G(S^2, B_r)$ is a solid bounded by two planar patches and some canal surfaces. (Canal surfaces are obtained by sweeping spheres, or balls, so that their centers lie on a curve in space.) Figure 2-2 shows a one-dimensional spine and its associated solid for a ball of radius r.

S^1 and S^2 need not be portions of lines or planes, respectively. If necessary, S^1 or S^2 can be extended to infinity, or closed upon itself, so that the resulting solid G is a half-space. The spine, along with the balls, also defines the symmetric axis transformation of such solids.

(b) Conformance. A regular feature of size or an IFOSa, F, conforms to the limits of size r_{LMC} and r_{MMC} if there exist two spines, S_ℓ corresponding to r_{LMC} and S_m corresponding to r_{MMC}, and two associated solids, $G_\ell = G(S_\ell, B_{r\text{LMC}})$ and $G_m = G(S_m, B_{r\text{MMC}})$, that satisfy two conditions described below.

(1) $H_\ell \subset H_m$

(2) $F \subset H_m - H_\ell$

In the above conditions, "$\subset$" indicates set containment and " – " indicates set difference.

If F is an external feature, then let $H_\ell = G_\ell$ and $H_m = G_m$. If F is an internal feature, then let H_ℓ be the complement of G_ℓ and H_m be the complement of G_m (see Figure 2-3).

NOTE: Additional guidance on the spines is detailed in Nonmandatory Appendix F.

(c) Actual Value. Two actual values are defined. The actual external (to the material) size of an external (respectively, internal) feature is the smallest (respectively, largest) size of the ball to which the feature conforms. The actual internal size is the largest (respectively, smallest) size of the ball to which the feature conforms. The size may be expressed as a radius or diameter, as appropriate to the application.

2.3.2 Variation of Size

Regular features of size and IFOSa are naturally parameterized by the size of the balls (spheres) used to construct the size tolerance zone. IFOSb must have an explicit parameterization where each size value corresponds to a boundary.

2.3.2.1 MMC Limit, Where Rule #1 of Y14.5 Applies

(a) Definition. Where Rule #1 applies, the MMC limit of the size tolerance is a bound on the allowed size of the perfect-form actual mating envelope of the feature of size. This can be modeled as a half-space formed by a cylinder (sphere/width) with size equal to the MMC size limit. The interior and boundary of this cylinder (sphere/width) is referred to as the MMC half-space.

(b) Conformance. If the feature of size is contained within MMC half-spaces (for external features) or contained within the complement of the MMC half-space (for internal features), the tolerance limit is satisfied.

(c) Actual Value. The actual mating size is the size of the unrelated actual mating envelope for the feature of size.

2.3.2.2 MMC Limit, Where Rule #1 of Y14.5 Does Not Apply

(a) Definition. If Rule #1 does not apply, the MMC limit of the size tolerance is a half-space formed by sweeping a ball having the diameter of the size limit along a spine of appropriate dimension for the feature (zero-dimensional point for a sphere feature of size, one-dimensional curve for a cylindrical feature of size, or a two-dimensional surface for a parallel plane feature of size). This is referred to as the MMC half-space.

(b) Conformance. For an external features, the tolerance limit is satisfied if the feature is contained within the MMC half-space for some spine. For internal features, the tolerance limit is satisfied if the feature is contained within the complement of the MMC half-space for some spine.

(c) Actual Value. The actual mating size is the diameter of the smallest ball that can be swept along a spine so that the feature is contained within the resulting half-space (for external features) or largest ball that can be swept along a spine so that the feature is contained within the complement of the resulting half-space (for internal features).

2.3.2.3 LMC Size Limit

(a) Definition. The LMC size limit describes a half-space formed by sweeping a ball having the diameter of the LMC size limit along a spine of appropriate dimension for the feature (zero-dimensional point for a sphere feature of size, one-dimensional curve for a cylindrical feature of size, or a two-dimensional surface for a parallel plane feature of size). The resulting volume is referred to as the LMC half-space.

(b) Conformance. For an external feature, the tolerance limit is satisfied if the feature is contained in the complement of the LMC half-space for some spine. For an internal feature, the tolerance limit is satisfied if the feature is contained within the LMC half-space for some spine.

(c) Actual Value. The actual minimum material size is the largest ball that can be swept along a spine so that the feature is contained within the complement of the resulting half-space (for external features) or smallest ball that can be swept along a spine so that the feature is contained within the resulting half-space (for internal features).

2.3.3 Actual Local Size Limits

In addition to the tolerance zone containment requirements for satisfying a size tolerance, requirements on the actual local size of a feature of size may be induced from the specification. ASME Y14.5 is not overly prescriptive in its definition of actual local size, stating merely that actual local size is "*any individual distance at any cross section of a feature of size.*" In some sections of the ASME Y14.5 standard, it appears this is a point-to-point distance, while in other sections there is reference to the actual local size of circular elements.

Both of these notions rely on cross sections, which are determined relative to a local size spine; this spine is one-dimensional (cylindrical features), two-dimensional (parallel plane features), or a point (spherical features).

2.3.3.1 Establishing the Local Size Spine. A local size spine must be tangent-continuous in order for cross sections to be taken along the entire feature. Per ASME Y14.5-2009

The derived median line/plane is made up of the center points of all cross sections/line segments of the feature normal (perpendicular) to the axis/center plane of the unrelated actual mating envelope. [1.3.30, 1.3.31]

As surface flaws may cause these center points to form a discontinuous line or plane, evaluation of actual local size requires constructing a tangent-continuous line or plane. Examples of non-unique center points or a tangent-discontinuous center line are shown in Figure 2-4. Because of these properties of the derived median line and plane, a local size spine is used that approximates the derived median line or plane, but is tangent-continuous.

NOTE: The local size spine can be thought of as a "well-behaved" derived median line or plane, possibly obtained through some smoothing of the derived median line or plane constructed using the ASME Y14.5 definition.

When straightness of the derived median line is evaluated (see para. 5.4.1.1), the nominally circular cross sections obtained from cylindrical features of size are evaluated to find the centers. In the absence of other specification, these centers will be the center of a "mating circle" in that cross section, i.e., an inscribed circle for an internal feature, and a circumscribed circle for an external feature.

2.3.3.2 Evaluation of Actual Local Size (Opposed Points). If actual local size is to be evaluated by the opposed points method, an actual local size exists:

– for every line perpendicular to the two-dimensional local size spine at the point this line intersects the spine (parallel plane features of size);

– for every line passing through the one-dimensional local size spine in any cross section perpendicular to the spine (cylindrical features of size); or

– for every line passing through the center point (spherical features of size).

These lines are referred to as evaluation lines. See Figure 2-5 for a graphical representation of actual local sizes on a cylindrical feature.

(a) Definition. The actual local size for a particular evaluation line is the Euclidean distance between the opposed points where the evaluation line intersects the actual feature. If there are more than two intersecting points, no size exists for this evaluation line.

(b) Conformance. If the distance between the two opposed points satisfies the size limits, this actual local size conforms to the tolerance.

(c) Actual Value. The actual value for an individual actual local size is the Euclidean distance between the two opposed points where the evaluation line intersects that actual feature.

NOTE: Conformance to the actual local size requirements is neither a necessary nor a sufficient condition for conformance to the size requirement based on swept spheres.

2.3.3.3 Evaluation of Actual Local Size (Circular Elements). If the actual local size is to be evaluated by the circular elements method, two actual local sizes exist for every point on the local size spine in the cross section perpendicular to the local size spine at that point (cylindrical features of size), or every plane passing through the center point (spherical features of size).

– Where Rule #1 does not apply, both "maximum material" and "least material" local sizes are of interest. If Rule #1 applies, only the "least material" local size is of interest.

– Cross sections are formed by using a cutting plane for cylindrical and spherical features of size.

– Circular element actual local size is not defined for parallel planes features of size.

(a) Definition. The actual least material local size in a particular cross section is the diameter of the minimum circumscribed circle (internal features) or the maximum inscribed circle (external features) corresponding to the actual feature in that cross section.

(b) Conformance. If the diameter of the defined circle(s) satisfies the limits of size, this actual local size conforms to the tolerance.

(c) Actual Value. The actual value for an actual local size (s) is the diameter of the defined circle(s).

NOTE: Conformance to the actual local size requirements is only intended to be an estimate of conformance to a size specification by the swept-sphere interpretation.

2.3.4 Continuous Features of Size

Where multiple features of size are indicated to be a continuous feature (⟨CF⟩), the MMC (perfect form) size definition remains the same for the portions(s) of the surface which form the continuous feature.

(a) For the opposed points definition of the actual local size, surface control only exists for those portions of the continuous feature that have opposed points as defined by two intersections of an evaluation line with the feature surface. For portions of the continuous feature with no opposed elements, no actual local size exists.

(b) For the circular element definition of the actual local size, surface control only exists where the inscribed or circumscribed circle is sufficiently constrained by the continuous feature in the cross section of evaluation.

2.3.5 Limits for Irregular Feature of Size (Type b)

As shown in Figure 2-6, IFOSb may be specified using profile tolerance. When the limits of "size" are defined by a profile tolerance, there is no unique size actual value for IFOSb. Nonmandatory Appendix D contains additional discussion.

2.3.6 Variation of Size Under Rule #1 for Irregular Features of Size

Rule #1 applies only to regular features of size. No standard syntax exists for requiring Rule #1 for irregular features of size.

Figure 2-1 Irregular Features of Size (Type a), Collection of Features

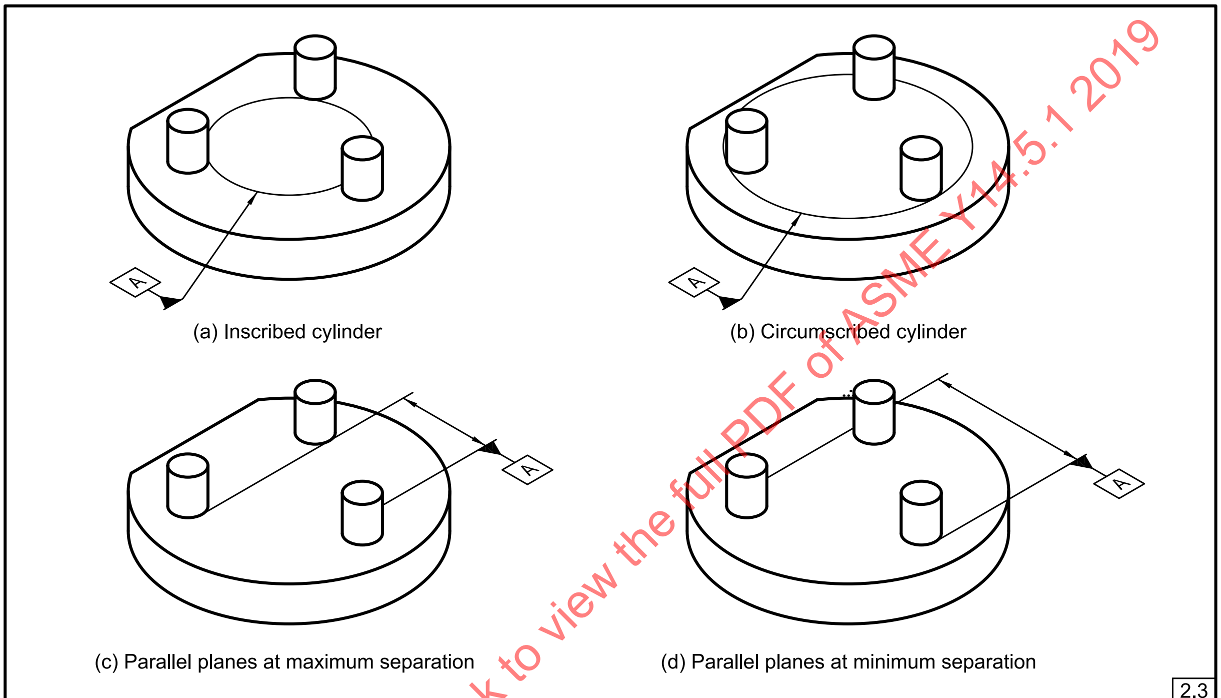


Figure 2-2 Symbols Used in the Definition of Size

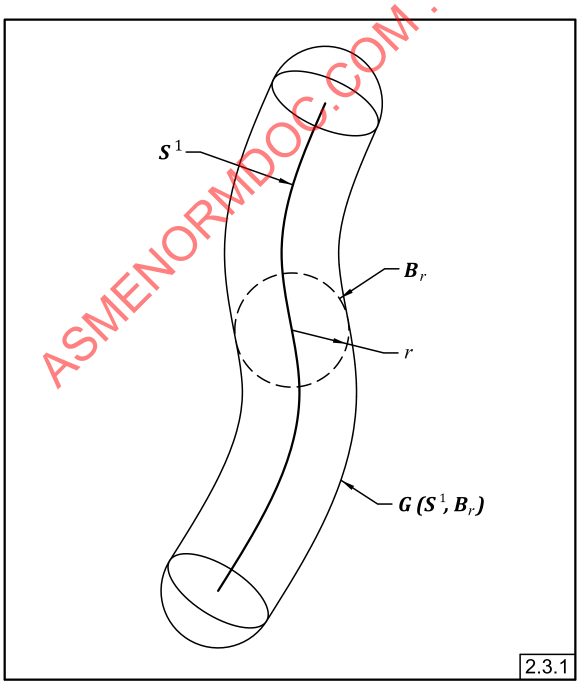


Figure 2-3 Conformance to Limits of Size, Internal Feature of Size

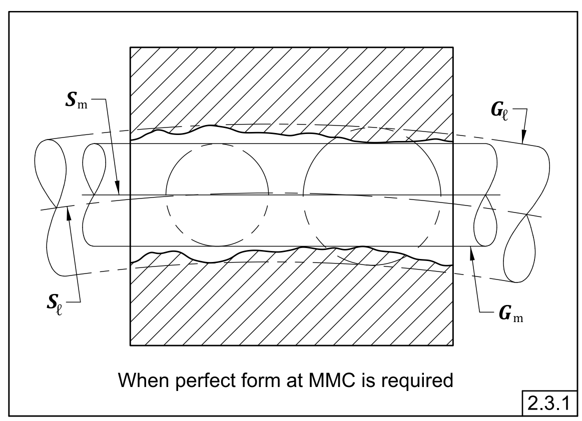


Figure 2-4 Examples of Surface Attributes Leading to Variations in the Derived Median Line

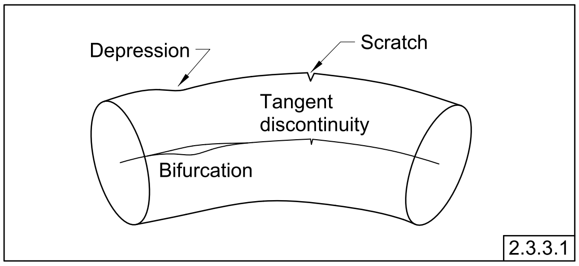


Figure 2-5 The Cutting Plane at a Point on a Local Size Spine, and Some of the Evaluation Lines in That Cutting Plane

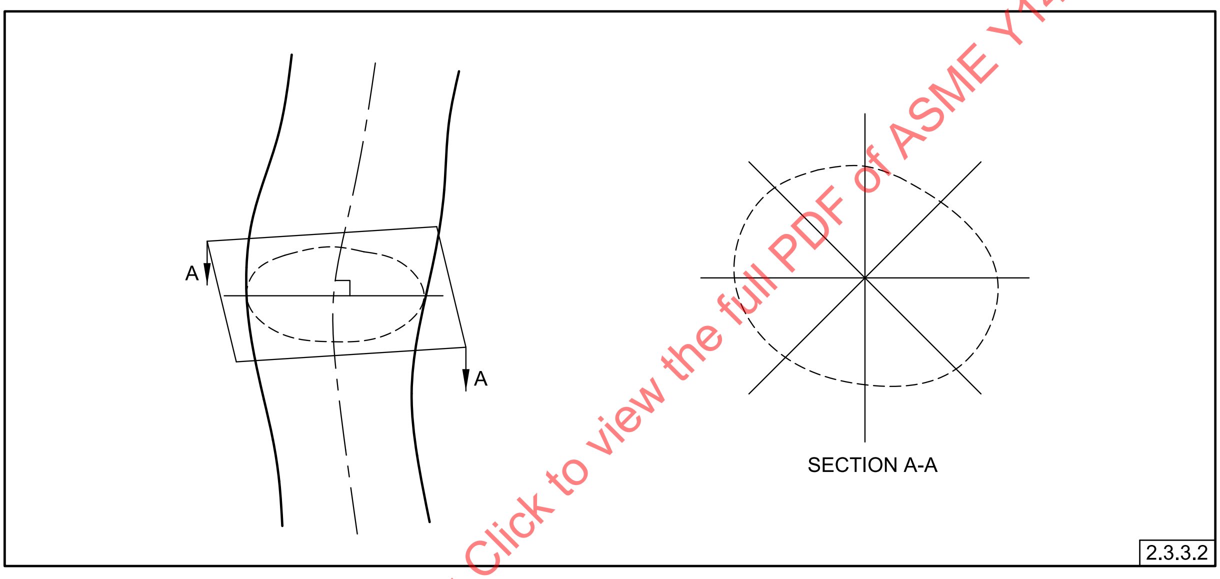
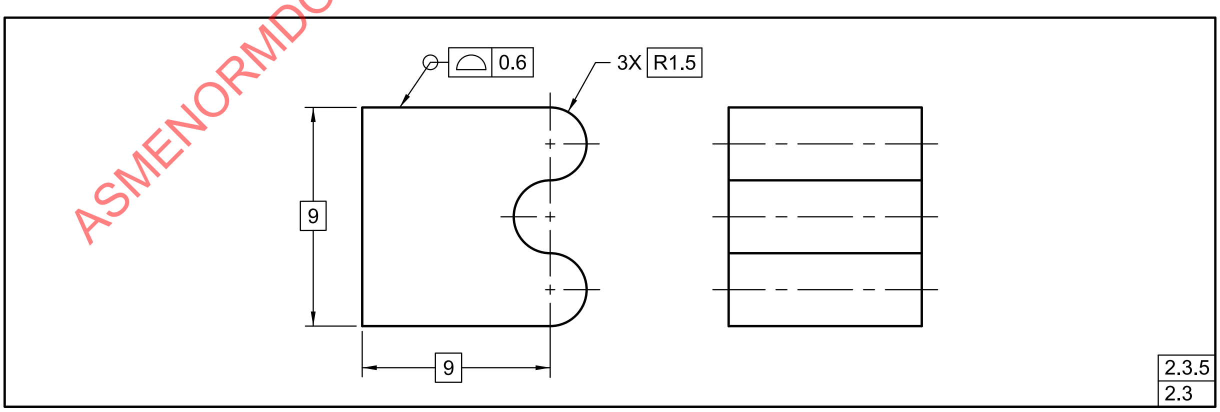


Figure 2-6 Profile of a Surface Tolerance Describing an External IFOSb



Section 3
Symbology

There are no concepts in Section 3 of ASME Y14.5-2009 that require mathematical definition.

Section 4
Datum Reference Frames

4.1 GENERAL

This Section contains mathematical methods for establishing datums and datum reference frames from datum features on a part. Datum reference frames are coordinate systems used to locate and orient part features.

4.2 CONCEPTS

In this Standard, sometimes it is explained that the part is assumed to be fixed in space and the datum reference frame is established in relation to the part. This approach can be contrasted to the explanation in ASME Y14.5-2009, where the datum reference frame is assumed to be fixed in space and the part is moved into the datum reference frame. The two approaches are different, but the end results are identical.

4.3 DEGREES OF FREEDOM

Per ASME Y14.5-2009

All parts have six degrees of freedom, three translational and three rotational, which may be constrained by datum feature references in a feature control frame. [4.2]

The three translational degrees of freedom are termed x (translation along X axis), y (translation along Y axis), and z (translation along Z axis). The three rotational degrees of freedom are termed u (rotation about the X axis), v (rotation about the Y axis), and w (rotation about the Z axis).

4.4 DATUM FEATURE SIMULATORS (THEORETICAL)

Datum features are identified on a drawing and referenced in an order of precedence in the feature control frame. Since datum features have manufactured variations, perfect datums cannot be directly derived from these imperfect features. Theoretical datum feature simulators are perfect, and unless otherwise specified (see para. 4.7.11), contact the imperfect datum feature at its extremities or high points. These theoretical datum feature simulators derive datums from the datum features, constrain the part's degrees of freedom, and create a datum reference frame. In ASME Y14.5, there are two types of datum feature simulators: physical and theoretical. This Standard will only reference the theoretical datum feature simulators.

4.4.1 Datum Feature Simulator Requirements

Per ASME Y14.5-2009

Datum feature simulators shall have the following requirements:

(a) perfect form

(b) basic orientation relative to one another for all the datum references in a feature control frame

(c) basic location relative to other datum feature simulators for all the datum references in a feature control frame, unless a translation modifier or movable datum target symbol is specified

(d) movable location when the translation modifier or the movable datum target symbol is specified

(e) fixed at the designated size, when MMB or LMB is specified

(f) adjustable in size, when the datum feature applies at RMB [4.5.2]

Referencing datum features in an order of precedence in a feature control frame establishes a series of datum feature simulators. The size, form, orientation, location, growth, or movement of these simulators is based on the datum feature modifier specified. This Standard expands the description of the datum feature simulator requirements as follows:

(a) They shall be the perfect inverse shape (opposite material counterpart) of the datum feature unless otherwise specified.

(b) They shall have perfect basic orientation relative to one another as referenced in a feature control frame.

(c) They shall have perfect basic location relative to one another as referenced in a feature control frame unless a translation modifier or movable datum target symbol is specified.

(d) They shall have movable location when the translation modifier or the movable datum target symbol is specified.

(e) They shall be fixed at the designated MMB size, when the datum feature is modified at MMB or fixed at the designated LMB size, when the datum feature is modified at LMB.

(f) They shall expand, contract, or otherwise progress, in their order of precedence, to make maximum contact with the datum feature when the datum feature is specified at RMB.

4.5 CONSTRAINING DEGREES OF FREEDOM

Per ASME Y14.5-2009

Where datum features are referenced in a feature control frame, the part is constrained in rotation and translation relative to the applicable datum feature simulators in the specified order of precedence with applicable modifiers that establish the datum reference frame. [4.4]

This establishes the relationship between the part and the datum reference frame.

4.5.1 Primary Datum Feature Types and Constrained Degrees of Freedom

The following primary datums are derived from the associated datum feature simulator:

(a) A planar datum feature (nominally flat) establishes a datum feature simulator that creates a datum plane and constrains three degrees of freedom (one translation and two rotations). Refer to Cases 3.1 through 3.18 in Table 4-4.

(b) A width as a datum feature (two opposed parallel surfaces) establishes a datum feature simulator that creates a datum center plane and constrains three degrees of freedom (one translation and two rotations). Refer to Cases 3.1 through 3.18 in Table 4-4.

(c) A spherical datum feature establishes a datum feature simulator that creates a datum center point and constrains three translational degrees of freedom. Refer to Cases 1.1 through 1.14 in Table 4-2.

(d) A cylindrical datum feature establishes a datum feature simulator that creates a datum axis and constrains four degrees of freedom (two translations and two rotations). Refer to Cases 2.1 through 2.20 in Table 4-3.

(e) A conical datum feature establishes a datum feature simulator that creates a datum axis and a datum point and constrains five degrees of freedom (three translations and two rotations). Refer to Cases 4.1 through 4.4 in Table 4-5.

(f) A datum feature of linear extruded shape establishes a datum feature simulator that creates a datum plane and a datum axis and constrains five degrees of freedom (two translations and three rotations). Refer to Cases 5.1 through 5.4 in Table 4-6.

(g) A complex datum feature establishes a datum feature simulator that creates a datum plane, datum point, and a datum axis and constrains six degrees of freedom (three translations and three rotations). Refer to Case 6.1 in Table 4-7.

4.5.2 Datum Feature Order of Precedence in a Datum Reference Frame

Datum features are specified in an order of precedence to relate the part to the datum reference frame. This order of precedence (e.g., primary, secondary, and tertiary) specified in the feature control frame determines which degrees of freedom each datum feature shall constrain. Unless otherwise specified, the primary datum feature constrains three or more of the six degrees of freedom. A lower precedence datum feature shall not constrain any degrees of freedom already established by any higher precedence datum feature. Therefore, the secondary datum feature, if specified, only constrains additional degrees of freedom that were not previously constrained by the primary datum feature. The tertiary datum feature, if specified, only constrains the remaining degree of freedom that was not previously constrained by the primary and secondary.

NOTE: It is possible lower precedence datum features are not needed because the higher precedence datum feature(s) have constrained all six degrees of freedom.

4.5.3 Partially Constrained Datum Reference Frame

A fully constrained datum reference frame is constrained in all three translational directions (x, y, and z) and all three rotations (u, v, and w). Depending on how a designated feature is toleranced from a datum reference frame, a partially constrained datum reference frame may be sufficient to define the tolerance zone for the designated feature. For example, if the datum reference frame is defined by only a plane (Case 3.1 in Table 4-4), then it is sufficiently constrained to define the parallelism tolerance zone for the designated feature with respect to the datum plane.

4.5.4 Datum Reference Frames for Composite Tolerances

In composite tolerancing, the feature-relating tolerances (lower segments of the feature control frame) control only the rotational degrees of freedom for the pattern. The datum reference frame for such a tolerance releases the translational degrees of freedom normally constrained by the procedures given above.

4.5.5 Customized Datum Reference Frames

ASME Y14.5-2009, subsections 4.22 and 4.23 address customized datum reference frames. Customized datum reference frames are used to override the degrees of freedom constrained by datum features in an order of precedence. The degrees of freedom to be constrained by each datum feature shall be explicitly stated by placing the designated degree of freedom (x, y, z, u, v, w) brackets behind each datum feature reference. This Standard does not show the possible combinations of customized datum reference frames.

4.6 TABULATION OF DATUM REFERENCE FRAMES

This subsection presents tables of datum reference frames organized by the geometry of the primary datum.

Table 4-1 presents the symbols used in the rest of the Section.

Tables 4-2 through 4-7 show all valid combinations of noncustomized datum reference frames and, for each case, the free degrees of freedom (DOF), the invariants, and the conditions under which the datum reference frame is valid. An invariant in a datum reference frame is a quantity (distance or angle) that does not change under unconstrained degrees of freedom allowed by that datum reference frame. (See Table 4-8.)

Coordinate system labels are somewhat arbitrary unless the coordinate system is labeled on the drawing. However, generally, the following conventions apply. If the primary datum is a point, it establishes the origin. If the primary datum is an axis, it establishes the *z* coordinate axis. If it is a plane, it establishes the *x*-*y* coordinate plane (and hence the direction of the *z* axis). Secondary and tertiary datums establish additional elements of the coordinate system.

The example in Figure 4-1 is a specific row from Table 4-3.

Figure 4-1 shows Case 2.8: a datum reference frame consisting of a primary datum axis, a secondary datum axis, and no tertiary datum. The validity conditions indicate that this case applies only if the two axes (A and B) are not equal and are parallel. The only free degree of freedom is translation along the *z* axis. As a result, the invariants include *x* and *y* coordinates, and all angle relationships between features and the datum reference frame.

4.7 CANDIDATE DATUM SETS AND CANDIDATE REFERENCE FRAME SETS

Sometimes multiple valid datum reference frames may be established from a set of datum features. This may happen for multiple reasons:

(a) A datum feature is referenced at MMB or LMB and the datum feature is allowed displacement due to its departure from MMB or LMB.

(b) A datum reference frame does not constrain all six degrees of freedom (see para. 4.5.3).

(c) The datum feature simulator does not make unique contact with the datum feature (if the datum feature "rocks"). Some examples of this are a nominally specified flat surface manufactured convex, a cylinder specified at RMB produced tapered or barreled, or a width specified at RMB produced tapered or diamond shaped.

The set of all possible candidate datums that can be established from a datum feature is called a *candidate datum set.* Since a datum feature may generate more than one datum, multiple datum reference frames may exist for a single feature control frame. The set of all possible candidate datum reference frames established from one or more datum features is called a candidate datum reference frame set.

4.7.1 Establishing a Candidate Datum Set

Paragraphs 4.7.2 through 4.7.6 establish the process for associating candidate datum sets with individual datum features. While a candidate datum set is associated with an individual datum feature, datum precedence is used in the definition. The candidate datums from these sets are used to construct the candidate datum reference frames as described in para. 4.7.8.

4.7.2 Types of Datum Features

The method of establishing datums depends on the type of datum feature (e.g., flat surface, cylinder, width, sphere), the datum feature precedence (primary, secondary, or tertiary), and sometimes the material condition of the datum reference (RMB, MMB, or LMB).

The following classification of datum features is used in paras. 4.7.3 through 4.7.6:

(a) planar datum features

(b) datum features of size that are cylinders, widths, and spheres

(1) referenced at RMB

(2) referenced at MMB

(3) referenced at LMB

This Standard does not specify how to establish candidate datum sets for screw threads, gears, or splines.

4.7.3 Planar Datum Features

Because of the imperfections in the datum feature's form, the candidate datum set may consist of more than one datum. This is equivalent to "rocking" the datum feature on a perfect plane. The definition below limits the amount that the datum feature can "rock" in a manner that is roughly proportional to the form variation of the datum feature.

(a) Primary Planar Datum Features. The candidate datum set for a nominally flat primary datum feature is defined by the following procedure:

(1) Consider a plane *P* which is an external surface of support for the datum feature. Let *C* be the set of contact points of the datum feature and *P.*

(2) Consider an arbitrary line *L* in *P*. Orthogonally project each point on the boundary of the datum feature onto *L*, giving the line segment L'. Consider regions of L' that are within some fraction *x* of the endpoints of L'. That is, if the length of L' is *n*, consider regions of L' within a distance *xn* of the endpoints of L'. Unless otherwise specified on the drawing, the value of *x* shall be 1/3. If all of the orthogonal projections of the points in *C* are within either single region, then plane *P* is rejected as a valid datum plane.

(3) Do this for all lines in *P.*

NOTE: Parallel lines will yield identical results.

If no line rejects *P,* then *P* is a candidate datum for the datum feature.

The procedure is illustrated in Figure 4-2, which shows one line direction *L.* The line segment *L′* is bounded by the projection of the datum feature onto *L.* The particular line direction illustrated in the figure does not reject *P* as a valid datum plane since the projections of the contact points onto *L* are not all in region 1 or all in region 2 of *L′*.

NOTE: Only the direction of *L* in the plane *P* is important. *P* is a candidate datum for the datum feature if it is not rejected by any line direction in *P*.

(b) Secondary Planar Datum Features Referenced at RMB. The candidate datum set for a secondary planar datum feature is determined by one of the following:

(1) If the primary datum is a point, use the procedure for a primary planar datum feature to establish the secondary datum.

(2) If the primary datum is an axis nominally perpendicular to the secondary datum, then, for each candidate datum in the candidate datum set for the primary datum feature, the secondary datum is the unique plane which is perpendicular to that primary datum and which forms a surface of support for the secondary datum feature.

(3) If neither (1) nor (2) applies, use the procedure for a primary planar datum feature modified in the following ways: Given a primary datum from the primary candidate datum set, each plane *P* being considered as a secondary datum must be basically oriented to the primary datum. Also, each line *L* in *P* being considered must be perpendicular to the direction vector of the primary datum. (Only one line in *P* must be considered.)

NOTE: If the secondary datum feature is referenced at MMB, LMB, or BASIC, the secondary datum feature simulator is located at the specified boundary or distance.

(c) Tertiary Planar Datum Features Referenced at RMB. If the first two datums leave a rotational degree of freedom, then the candidate datum set is formed by the procedure for a primary planar datum feature modified such that each plane *P* being considered must be basically oriented relative to the datums of higher precedence, and one line *L* is to be considered, which must be perpendicular to the axis established by the higher precedence datums. If the first two datums do not leave a rotational degree of freedom, the candidate datum set consists of the plane which is basically oriented relative to the datums of higher precedence and which forms a surface of support for the datum feature.

NOTE: If the tertiary datum feature is referenced at MMB, LMB, or BASIC, the tertiary datum feature simulator is located at the specified boundary or distance.

4.7.4 Datum Features of Size Referenced at RMB

(a) Cylinder (Both Internal and External). The candidate datum set for a cylinder is the set of axes of all datum feature simulators of the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically oriented and, if applicable, basically located to the higher precedence datums.

(b) Width (Both Internal and External). The candidate datum set for a width is the set of all center planes of all datum feature simulators of the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically oriented and, if applicable, basically located to the higher precedence datums.

Figure 4-3 shows an example of a tertiary datum feature simulator specified at RMB oriented and located to higher precedence datums. Datum center plane C in the figure must be established from the datum feature under the constraint that the simulator is oriented to datum plane A and oriented and located to datum axis B.

(c) Sphere (Both Internal and External). The candidate datum set for a sphere is the set of center points of all datum feature simulators of the datum feature.

4.7.5 Datum Features of Size Referenced at MMB

(a) Cylinder [External] {Internal}. The candidate datum set for a cylinder is the set of axes of all datum feature simulators of MMB size that [enclose] {are enclosed within} the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically oriented and, if applicable, basically located to the higher precedence datums.

(b) Width [External] {Internal}. The candidate datum set for a width is the set of center planes of all datum feature simulators of MMB size that [enclose] {are enclosed within} the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically oriented and, if applicable, basically located to the higher precedence datums.

(c) Sphere [External] {Internal}. The candidate datum set for a sphere is the set of center points of all datum feature simulators of MMB size that [enclose] {are enclosed within} the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically located to the higher precedence datums.

4.7.6 Datum Features of Size Referenced at LMB

(a) Cylinder [External] {Internal}. The candidate datum set for a cylinder is the set of axes of all datum feature simulators of LMB size that [are enclosed within] {enclose} the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically oriented and, if applicable, basically located to the higher precedence datums.

(b) Width [External] {Internal}. The candidate datum set for a width is the set of center planes of all datum feature simulators of LMB size that [are enclosed within] {enclose} the datum feature. For secondary or tertiary datum features, the simulators are constrained

to be basically oriented and, if applicable, basically located to the higher precedence datums.

(c) Sphere [External] {Internal}. The candidate datum set for a sphere is the set of center points of all datum feature simulators of LMB size that [are enclosed within] {enclose} the datum feature. For secondary or tertiary datum features, the simulators are constrained to be basically located to the higher precedence datums.

4.7.7 Translation Modifier

Per ASME Y14.5-2009

Where it is necessary to indicate that the basic location of the datum feature simulator is unlocked and the datum feature simulator is able to translate to fully engage the feature, the translation modifier is added to the feature control frame following the datum feature reference and any other applicable modifiers. [4.11.10]

The datum feature simulator is constrained to be basically oriented but not basically located to the higher precedence datums. See Figure 4-4.

4.7.8 Establishing a Candidate Datum Reference Frame Set

The construction of a particular candidate datum reference frame shall proceed as follows:

(a) A primary datum is selected from the candidate datum set associated with the primary datum feature.

(b) If a secondary datum is called out, the choice of primary datum establishes, by the rules of the former subsections, a candidate datum set for the secondary datum feature. A secondary datum is chosen from this set.

(c) Similarly, if a tertiary datum is called out, the choice of primary and secondary datums establishes a candidate datum set for the tertiary datum feature. A tertiary datum is chosen from this last set.

All the candidate datum reference frames established in this manner constitute the candidate datum reference frame set.

4.7.9 Conformance and Actual Value

For tolerances that reference a datum reference frame, if the feature does not violate the constraints defined by the tolerance for at least one candidate datum reference frame in the candidate datum reference frame set, then the feature is in conformance to the tolerance. There is a candidate actual value associated with each candidate datum reference frame in the candidate datum reference frame set. The actual value associated with the tolerance is the minimum candidate actual value.

4.7.10 Simultaneous Requirements

Per ASME Y14.5-2009

A simultaneous requirement is where two or more geometric tolerances apply as a single pattern or part requirement. A simultaneous requirement applies to position and profile tolerances that are located by basic dimensions, related to common datum features referenced in the same order of precedence at the same boundary conditions. [4.19]

All features with simultaneous requirements must use the same candidate datum reference frame in the candidate datum reference frame set.

4.7.11 Alternate Stabilization Procedures

In accordance with ASME Y14.5-2009, if irregularities on a datum feature are such that the part is unstable when brought into contact with the corresponding datum feature simulator, the default stabilization procedure is per the candidate datum set as outlined in this Standard. ASME Y14.5-2009 does allow for different stabilization procedures to be specified. When a single solution that minimizes the separation between the feature and the simulator is specified the default procedure is a constrained L2 for datum features of size and the constrained L2 applied to the external envelope for planar datum features.

The background and details of this procedure can be found in Nonmandatory Appendix B.

Table 4-1 Symbols for Datum Reference Frame Tables

Symbol	Description
A	Primary datum
B	Secondary datum
C	Tertiary datum
PT	Point
AX	Axis
PL	Plane
{LI ...}	Line through ...
{LI ... : ... }	Line through ... such that ... is true
≠	Not coincidental with
⊂	Contained within
⊄	Not contained within
||	Parallel with
⊥	Perpendicular to
∧	Logical AND
∨	Logical OR (one or the other, or both)
¬	Logical NOT
∩	Intersection
x, y, z	Position in a Cartesian coordinate system
u, v, w	Rotation about x, y, z axis, respectively
γ_z	Angle relative to datum axis z
r	Spherical radius: $\sqrt{x^2 + y^2 + z^2}$
ρ_z	Cylindrical radius: $\sqrt{x^2 + y^2}$
—	No entry (e.g., not applicable, none)

Table 4-2 Point as Primary Datum (Spherical Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
1.1	PT	—	—	u, v, w	*r*	—
1.2	PT	PT	—	w	ρ_z, z, γ_z	A ≠ B
1.3	PT	PT	PT	—	All	(A ≠ B) ∧ (C ⊄ {LI AB})
1.4	PT	PT	AX	—	All	(A ≠ B) ∧ (C ≠ {LI AB})
1.5	PT	PT	PL	—	All	(A ≠ B) ∧ ¬(C ⊥ {LI AB})
1.6	PT	AX	—	—	All	A ⊄ B
1.7	PT	AX	—	w	ρ_z, z, γ_z	A ⊂ B
1.8	PT	AX	PT	—	All	(A ⊂ B) ∧ (C ⊄ B)
1.9	PT	AX	AX	—	All	(A ⊂ B) ∧ (B ≠ C)
1.10	PT	AX	PL	—	All	(A ⊂ B) ∧ ¬ (B ⊥ C)
1.11	PT	PL	—	w	ρ_z, z, γ_z	—
1.12	PT	PL	PT	—	All	C ⊄ {LI A: LI ⊥ B}
1.13	PT	PL	AX	—	All	C ≠ {LI A: LI ⊥ B}
1.14	PT	PL	PL	—	All	¬ (C ∥ B)

Table 4-3 Axis as Primary Datum (Cylindical Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
2.1	AX	—	—	z, w	ρ_z, γ_z	—
2.2	AX	PT	—	—	All	B ⊄ A
2.3	AX	PT	—	w	ρ_z, z, γ_z	B ⊂ A
2.4	AX	PT	PT	—	All	(B ⊂ A) ∧ (C ⊄ A)
2.5	AX	PT	AX	—	All	(B ⊂ A) ∧ (A ≠ C)
2.6	AX	PT	PL	—	All	(B ⊂ A) ∧ ¬ (A ⊥ C)
2.7	AX	AX	—	—	All	(A ≠ B) ∧ ¬ (A ∥ B)
2.8	AX	AX	—	z	x, y, u, v, w	(A ≠ B) ∧ (A ∥ B)
2.9	AX	AX	PT	—	All	(A ≠ B) ∧ (A ∥ B)
2.10	AX	AX	AX	—	All	(A ≠ B) ∧ (A ∥ B) ∧ ¬ (A ∥ *C*)
2.11	AX	AX	PL	—	All	(A ≠ B) ∧ (A ∥ B) ∧ ¬ (A ∥ *C*)
2.12	AX	PL	—	—	All	¬ ((A ∥ B) ∨ (A ⊥ B)
2.13	AX	PL	—	z	x, y, u, v, w	A ∥ B (including A ⊂ B)
2.14	AX	PL	—	w	ρ_z, z, γ_z	A ⊥ B
2.15	AX	PL	PT	—	All	A ∥ B
2.16	AX	PL	PT	—	All	(A ⊥ B) ∧ (C ⊄ A)
2.17	AX	PL	AX	—	All	(A ∥ B) ∧ ¬ (A ∥ C)
2.18	AX	PL	AX	—	All	(A ⊥ B) ∧ (A ≠ C)
2.19	AX	PL	PL	—	All	(*A* ∥ B) ∧ ¬ (*A* ∥ *C*)
2.20	AX	PL	PL	—	All	(A ⊥ B) ∧ ¬(A ⊥ C)

Table 4-4 Plane as Primary Datum (Planar or Width Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
3.1	PL	—	—	x, y, w	z, γ_z	—
3.2	PL	PT	—	w	ρ_z, z, γ_z	—
3.3	PL	PT	PT	—	All	C ⊄ {LI B: LI ⊥ A}
3.4	PL	PT	AX	—	All	C ≠ {LI B: LI ⊥ A}
3.5	PL	PT	PL	—	All	¬ (A ‖ C)
3.6	PL	AX	—	—	All	¬ ((A ‖ B) ∨ (A ⊥ B))
3.7	PL	AX	—	w	ρ_z, z, γ_z	A ⊥ B
3.8	PL	AX	—	x	y, z, u, v, w	A ‖ B
3.9	PL	AX	PT	—	All	(A ⊥ B) ∧ (C ⊄ B)
3.10	PL	AX	PT	—	All	A ‖ B
3.11	PL	AX	AX	—	All	(A ⊥ B) ∧ (B ≠ C)
3.12	PL	AX	AX	—	All	(A ‖ B) ∧ ¬ (B ‖ C)
3.13	PL	AX	PL	—	All	(A ⊥ B) ∧ ¬ (B ⊥ C)
3.14	PL	AX	PL	—	All	(A ‖ B) ∧ ¬ (B ‖ C)
3.15	PL	PL	—	x	y, z, u, v, w	¬ (A ‖ B)
3.16	PL	PL	PT	—	All	¬ (A ‖ B)
3.17	PL	PL	AX	—	All	¬(A ‖ B) ∧ ¬ (C ‖ {LI (A ∩ B)})
3.18	PL	PL	PL	—	All	¬(A ‖ B) ∧ ¬ (C ‖ {LI (A ∩ B)})

Table 4-5 Coincident Axis and Point as Primary Datum (Conical Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
4.1	AX & PT	—	—	w	ρ_z, z, γ_z	—
4.2	AX & PT	PT	—	—	All	B ⊄ A
4.3	AX & PT	AX	—	—	All	A ≠ B
4.4	AX & PT	PL	—	—	All	¬ (A ⊥ B)

Table 4-6 Axis and Plane as Primary Datum (Linear Extruded Shape Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
5.1	AX & PL	—	—	z	x, y, u, v, w	—
5.2	AX & PL	PT	—	—	All	—
5.3	AX & PL	AX	—	—	All	¬ (A ‖ B)
5.4	AX & PL	PL	—	—	All	¬ (A ‖ B)

Table 4-7 Axis Point and Plane as Primary Datum (Complex Datum Feature)

Case	Datums A	Datums B	Datums C	Free DOF	Invariants	Validity Conditions
6.1	AX, PT & PL	—	—	—	All	—

Table 4-8 Generic Invariant Cases

Index	Invariant Cases	Case Number(s)
1	r	1.1
2	ρ_z, γ_z	2.1
3	ρ_z, z, γ_z	1.2, 1.7, 1.11, 2.3, 2.14, 3.2, 3.7, 4.1
4	z, γ_z	3.1
5	x, y, u, v, w or y, z, u, v, w	2.8, 2.13, 3.8, 3.15, 5.1
6	All	All others

Figure 4-1 Example From Table 4-3 — Axis as Primary Datum

Case	Datums A	B	C	Free DOF	Invariants	Validity Conditions
2.8	AX	AX	—	z	x, y, u, v, w	(A ≠ B) ∧ (A ‖ B)

Figure 4-2 Example of Testing Whether a Plane Is a Valid Datum Plane

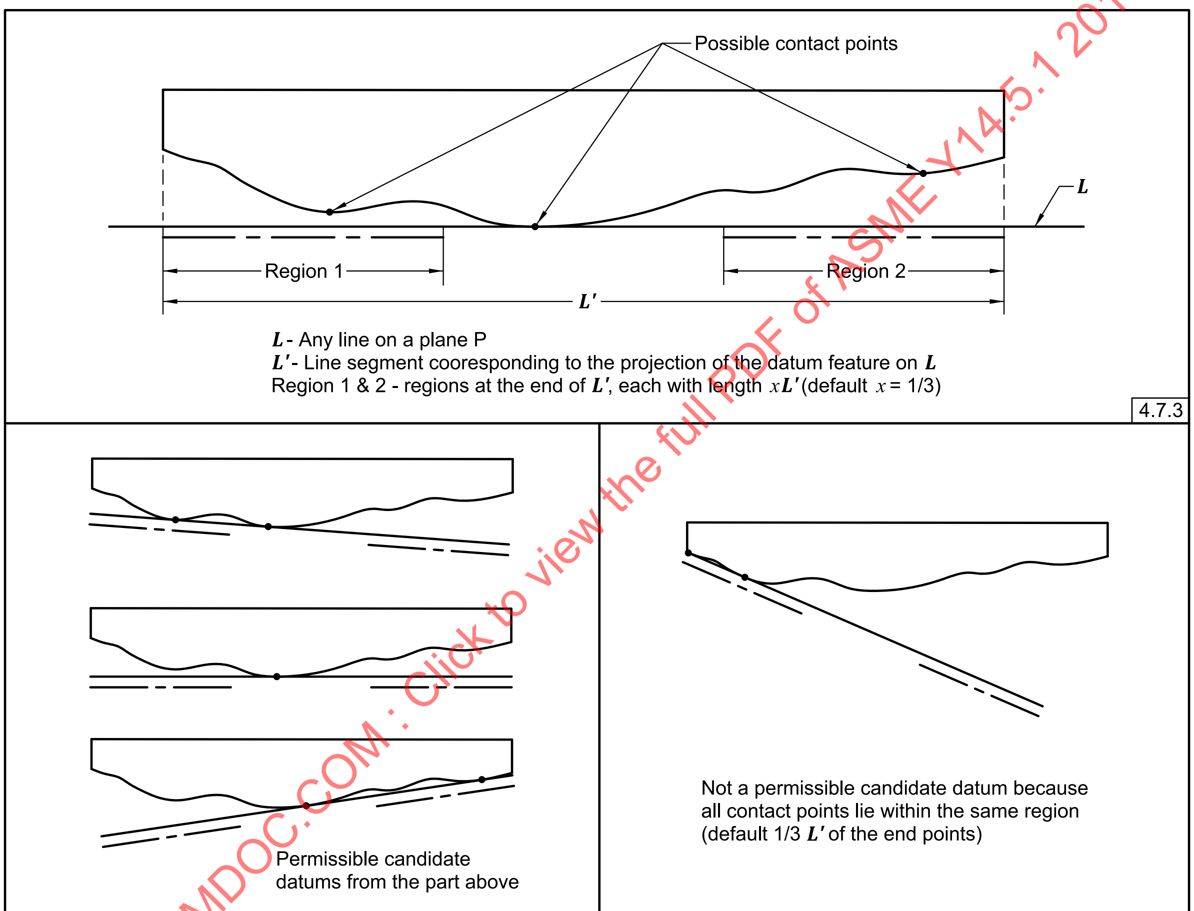


Figure 4-3 Tertiary Datum Feature Simulator Is Basically Located and Oriented

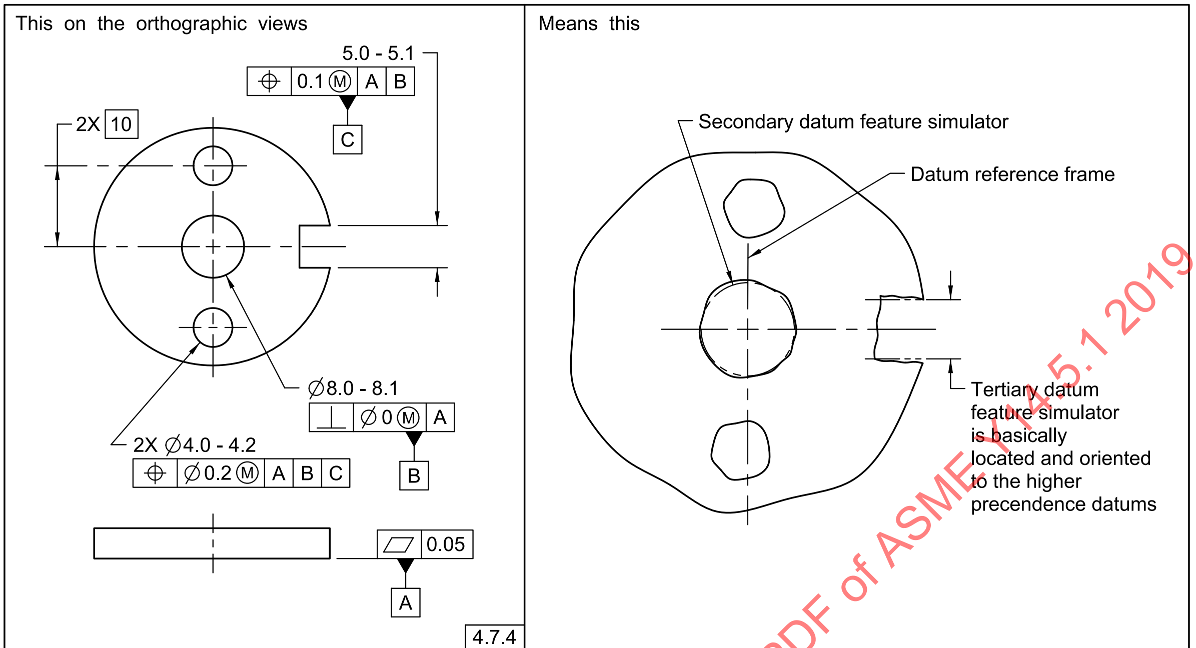
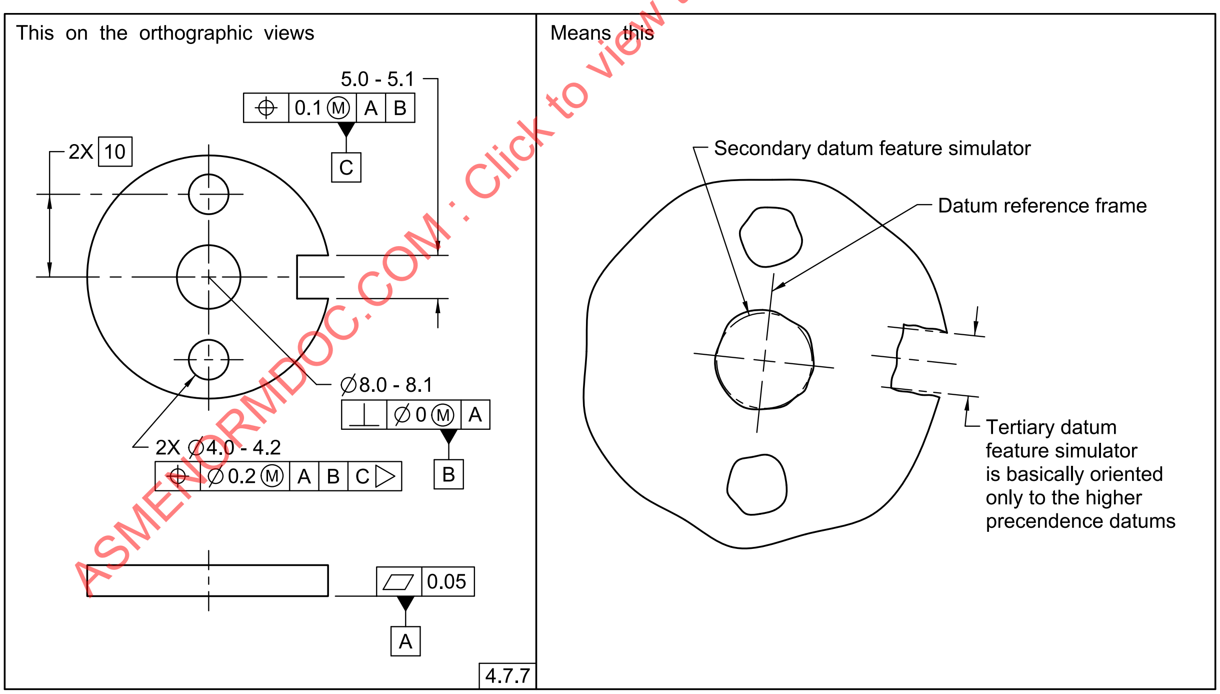


Figure 4-4 Example of Translation Modifier



Section 5
Tolerances of Form

5.1 GENERAL

This Section establishes the principles and methods for the mathematical evaluation of ASME Y14.5-2009 dimensioning and tolerancing to control the form of features.

5.2 FORM CONTROL

Per ASME Y14.5-2009

Form tolerances control straightness, flatness, circularity, and cylindricity. When specifying a form tolerance, consideration must be given to the control of form already established through other tolerances such as size (Rule #1), orientation, runout, and profile controls. [5.2]

5.3 SPECIFYING FORM TOLERANCES

Per ASME Y14.5-2009

Form tolerances critical to function and interchangeability are specified where the tolerances of size do not provide sufficient control. A tolerance of form may be specified where no tolerance of size is given (e.g., in the control of flatness after assembly of the parts). A form tolerance specifies a zone within which the considered feature, its line elements, its derived median line, or its derived median plane must be contained. [5.3]

While the shape of the tolerance zone is defined (a cylinder, a zone bounded by two concentric cylinders, a zone bounded by two concentric circles, a zone bounded by two parallel planes, or a zone bounded by two parallel lines), the extent of the tolerance zone (e.g., the length of the cylinder) must also be considered. The following two cases are to be considered:

(a) The extent of the tolerance zone is restricted to control a limited area or length of the surface shown by a chain line drawn parallel to the surface profile dimensioned for length and location.

(b) In all other cases, the extent of the tolerance zone is limited to the actual feature surface. For a derived median line or a derived median plane the extent is defined by projecting the actual surface points onto the derived median line or derived median plane.

5.4 FORM TOLERANCES

Per ASME Y14.5-2009

Form tolerances are applicable to single (individual) features or elements of single features; therefore, form tolerances are not related to datums. The following subparagraphs cover the particulars of the form tolerances: straightness, flatness, circularity, and cylindricity. [5.4]

5.4.1 Straightness

Per ASME Y14.5-2009

Straightness is a condition where an element of a surface, or derived median line, is a straight line. A straightness tolerance specifies a tolerance zone within which the considered element of a surface or derived median line must lie. A straightness tolerance is applied in the view where the elements to be controlled are represented by a straight line. [5.4.1]

5.4.1.1 Straightness at RFS of a Cylinder (Applied to a Derived Median Line)

(a) Definition. A straightness tolerance at RFS of a cylinder specifies that the derived median line must lie within some cylindrical zone whose diameter is the specified tolerance. A straightness zone for a derived median line is a cylindrical volume consisting of all points $\vec{P}$ satisfying the condition

$$\left|\hat{\boldsymbol{T}} \times \left(\vec{\boldsymbol{P}} - \vec{\boldsymbol{A}}\right)\right| \le \frac{t}{2}$$

where

$\vec{A}$ = any point on the center line of the straightness zone

$\hat{T}$ = the direction vector of the straightness axis

t = the diameter of the straightness zone

(b) Conformance. A cylindrical feature conforms to a straightness tolerance at RFS t_0 if all points of the derived median line lie within a straightness zone as defined above with $t = t_0$. That is, there exist $\hat{T}$ and $\vec{A}$ such that with $t = t_0$, all points of the derived median line are within the straightness tolerance zone.

(c) Actual Value. The actual value of straightness at RFS of a cylinder is the smallest straightness tolerance to which the derived median line will conform.

5.4.1.2 Straightness at MMC/LMC of a Cylinder (Applied to a Derived Median Line)

(a) Definition. A straightness tolerance at MMC/LMC of a cylinder specifies that the actual surface must not violate the virtual condition boundary. Per ASME Y14.5-2009

The collective effect of size and form variation can produce a virtual condition or outer or inner boundary equal to the MMC/LMC *size plus the straightness tolerance.* [5.4.1.2]

No resolved geometry interpretation is provided for MMC or LMC tolerances. The surface interpretation for straightness at MMC/LMC of a cylinder is that the surface of an actual cylindrical feature must lie within (or without for a hole) the virtual condition boundary.

(b) Conformance. A cylindrical feature conforms to a straightness tolerance at MMC/LMC if all surface points lie within the virtual condition boundary (or without for a hole).

(c) Actual Value. The actual value of straightness at MMC/LMC of a cylinder is the smallest straightness tolerance to which feature will conform.

5.4.1.3 Straightness of Surface Line Elements

(a) Definition. A straightness tolerance for the line elements of a feature specifies that each line element must lie in a zone bounded by two parallel lines which are separated by the specified tolerance and which are in the cutting plane defining the line element.

When a straightness tolerance is applied to the longitudinal elements of a cylindrical feature, the cutting plane contains the axis of the unrelated actual mating envelope of the cylinder. For a planar surface, a straightness tolerance is applied in the view where the elements to be controlled are represented by a straight line.

A straightness zone for a surface line element is an area between parallel lines consisting of all points $\vec{P}$ satisfying the condition

$$\left|\hat{T} \times \left(\vec{P} - \vec{A}\right)\right| \le \frac{t}{2}$$

and

$$\hat{C}_P \cdot \left(\vec{P} - \vec{P_S}\right) = 0$$

$$\hat{C}_P \cdot \left(\vec{A} - \vec{P_S}\right) = 0$$

$$\hat{C}_P \cdot \hat{T} = 0$$

where

$\vec{A}$ = any point on the center line of the straightness zone

$\hat{C}_P$ = the normal to the cutting plane; perpendicular to $\hat{N}$, and perpendicular to the mating axis for cylindrical surfaces or parallel to the view surface normal for planar surfaces

$\hat{N}$ = the mating envelope surface normal

$\vec{P_S}$ = a point on the surface, contained by the cutting plane

$\hat{T}$ = the direction vector of the center line of the straightness zone

t = the size of the straightness zone (the separation between the parallel lines)

Figure 5-1 illustrates a straightness zone for surface line elements of a cylindrical feature. Figure 5-2 illustrates a straightness zone for surface line elements of a planar feature.

(b) Conformance. A surface line element conforms to the straightness tolerance t_0 for a cutting plane if all points of the surface line element lie within some straightness zone as defined above with $t = t_0$. That is, there exist $\hat{T}$ and $\vec{A}$ such that with $t = t_0$, all points of the surface line element are within the straightness tolerance zone.

A surface conforms to the straightness tolerance t_0 if it conforms simultaneously for all toleranced surface line elements corresponding to the actual mating envelope.

(c) Actual Value. The actual value of straightness for a surface is the smallest straightness tolerance to which the surface will conform.

5.4.2 Flatness

Per ASME Y14.5-2009

Flatness is the condition of a surface or derived median plane having all elements in one plane. A flatness tolerance specifies a tolerance zone defined by two parallel planes within which the surface or derived median plane must lie. [5.4.2]

5.4.2.1 Flatness of a Planar Surface

(a) Definition. A flatness tolerance of a plane specifies that all points of the surface must lie in some zone bounded by two parallel planes which are separated by the specified tolerance.

A flatness zone is a volume consisting of all points $\vec{P}$ satisfying the condition

$$\left|\hat{T} \cdot \left(\vec{P} - \vec{A}\right)\right| \le \frac{t}{2}$$

where

$\vec{A}$ = any point on the mid-plane of the flatness zone

$\hat{T}$ = the direction vector of the parallel planes defining the flatness zone

t = the size of the flatness zone (the separation of the parallel planes)

(b) Conformance. A feature conforms to a flatness tolerance t_0 if all points of the feature lie within some flatness zone as defined above, with $t = t_0$. That is, there exist $\hat{T}$ and

$\overrightarrow{A}$ such that with $t = t_0$, all points of the feature are within the flatness tolerance zone.

(c) Actual Value. The actual value of flatness for a planar surface is the smallest flatness tolerance to which the surface will conform.

5.4.2.2 Flatness at RFS of a Width

(a) Definition. A flatness tolerance at RFS of a width specifies that all points of the derived median plane must lie in some zone bounded by two parallel planes which are separated by the specified tolerance.

A flatness zone is a volume consisting of all points $\overrightarrow{P}$ satisfying the condition

$$\left|\hat{T}\cdot\left(\overrightarrow{P} - \overrightarrow{A}\right)\right| \leq \frac{t}{2}$$

where

$\overrightarrow{A}$ = any point on the mid-plane of the flatness zone

$\hat{T}$ = the direction vector of the parallel planes defining the flatness zone

t = the size of the flatness zone (the separation of the parallel planes)

(b) Conformance. A width conforms to a flatness tolerance t_0 at RFS if all points of the derived median plane lie within some flatness zone as defined above, with $t = t_0$. That is, there exist $\hat{T}$ and $\overrightarrow{A}$ such that with $t = t_0$, all points of the derived median plane are within the flatness tolerance zone.

(c) Actual Value. The actual value of flatness at RFS for a width is the smallest flatness tolerance to which the derived median plane will conform.

5.4.2.3 Flatness at MMC/LMC of a Width Feature

(a) Definition. A flatness tolerance at MMC/LMC of a width specifies that actual surface must not violate the virtual condition boundary. The collective effect of size and form variation can produce a virtual condition boundary equal to the MMC/LMC size plus/minus the flatness tolerance.

No resolved geometry interpretation is provided for MMC or LMC tolerances. The surface interpretation definition for flatness at MMC/LMC of a width is that the actual width feature must lie within (or without for a slot) the virtual condition boundary.

(b) Conformance. A width conforms to a flatness tolerance at MMC/LMC if all surface points of the feature lie within the virtual/resultant condition boundary (or without for a slot).

(c) Actual Value. The actual value of flatness at MMC/LMC for a width is the smallest flatness tolerance to which the derived median plane will conform.

5.4.3 Circularity (Roundness)

Per ASME Y14.5-2009

Circularity is a condition of a surface where

(a) for a feature other than a sphere, all points of the surface intersected by any plane perpendicular to an axis or spine (curved line) are equidistant from that axis or spine;

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

A circularity tolerance specifies a tolerance zone bounded by two concentric circles within which each circular element of the surface must lie, and applies independently at any plane described in (a) and (b) above. [5.4.3]

(a) Definition. A circularity tolerance specifies that all points of each circular element of the surface must lie in some zone bounded by two concentric circles whose radii differ by the specified tolerance. Circular elements are obtained by taking cross sections perpendicular to some spine. For a sphere, the spine is zero-dimensional (a point), and for a cylinder, cone, torus, or other swept-sphere shape, the spine is one-dimensional (a simple, non-self-intersecting, tangent-continuous curve). The concentric circles defining the circularity zone are centered on, and in a plane perpendicular to, the spine.

A circularity zone at a given cross section is an annular area consisting of all points $\overrightarrow{P}$ satisfying the following conditions:

$$\hat{T}\cdot\left(\overrightarrow{P} - \overrightarrow{A}\right) = 0$$

and

$$\left|\left|\overrightarrow{P} - \overrightarrow{A}\right| - r\right| \leq \frac{t}{2}$$

where

$\overrightarrow{A}$ = any point on the spine

r = a radial distance (which may vary between circular elements) from the spine to the center of the circularity zone ($r > 0$ for all circular elements)

$\hat{T}$ = for a cylinder or cone, a unit vector that is tangent to the spine at $\overrightarrow{A}$. For a sphere, $\hat{T}$ is a unit vector that points radially in all directions from $\overrightarrow{A}$

t = the size of the circularity zone

Figure 5-3 illustrates a circularity zone for a circular element of a cylindrical or conical feature.

(b) Conformance. A cylindrical or conical feature conforms to a circularity tolerance t_0 if there exists a one-dimensional spine such that at each point $\overrightarrow{A}$ of the spine the circular element perpendicular to the

tangent vector $\hat{T}$ at $\overrightarrow{A}$ conforms to the circularity tolerance t_0. That is, for each circular element there exist $\overrightarrow{A}$ and r such that with $t = t_0$, all points of the circular element are within the circularity tolerance zone.

A spherical feature conforms to a circularity tolerance t_0 if there exists a point (a zero-dimensional spine) such that each circular element in each cutting plane containing the point conforms to the circularity tolerance t_0. That is, for each circular element there exist $\hat{T}$, r, and a common $\overrightarrow{A}$ such that with $t = t_0$, all points of the circular element are within the circularity tolerance zone.

(c) Actual Value. The actual value of circularity for a feature is the smallest circularity tolerance to which the feature will conform.

5.4.4 Cylindricity

Per ASME Y14.5-2009

Cylindricity is a condition of a surface of revolution in which all points of the surface are equidistant from a common axis. A cylindricity tolerance specifies a tolerance zone bounded by two concentric cylinders within which the surface must lie. In the case of cylindricity, unlike that of circularity, the tolerance applies simultaneously to both circular and longitudinal elements of the surface (the entire surface). [5.4.4]

NOTE: The cylindricity tolerance is a composite control of form which includes circularity, straightness, and taper of a cylindrical feature.

(a) Definition. A cylindricity tolerance specifies that all points of the surface must lie in some zone bounded by two coaxial cylinders whose radii differ by the specified tolerance.

A cylindricity zone is a volume between two coaxial cylinders consisting of all points $\overrightarrow{P}$ satisfying the condition

$$\left| \left| \hat{T} \times \left(\overrightarrow{P} - \overrightarrow{A} \right) \right| - r \right| \leq \frac{t}{2}$$

where

$\overrightarrow{A}$ = any point on the cylindricity axis

r = the radial distance from the cylindricity axis to the center of the zone

$\hat{T}$ = the direction vector of the cylindricity axis

t = the size of the cylindricity zone

(b) Conformance. A feature conforms to a cylindricity tolerance t_0 if all points of the feature lie within some cylindricity zone as defined above with $t = t_0$. That is, there exist $\hat{T}$, $\overrightarrow{A}$, and r such that with $t = t_0$, all points of the feature are within the cylindricity tolerance zone.

(c) Actual Value. The actual value of cylindricity for a surface is the smallest cylindricity tolerance to which it will conform.

Figure 5-1 Evaluation of Straightness of a Cylindrical Surface

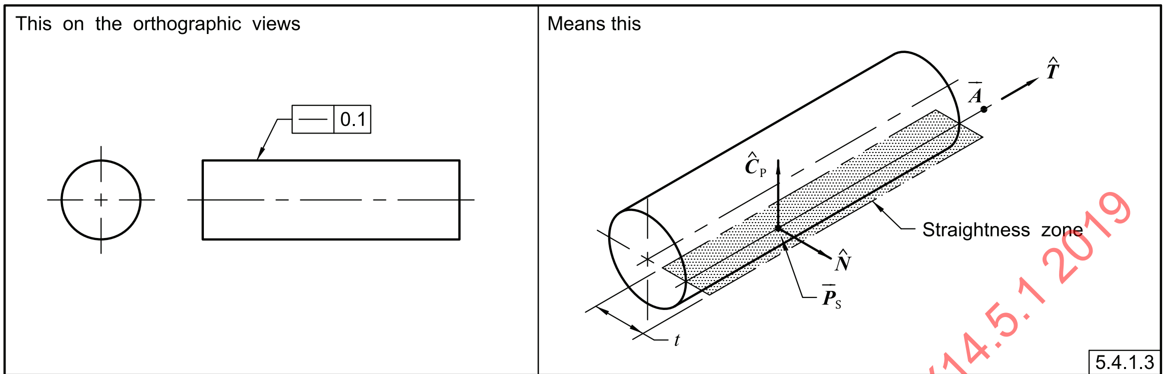


Figure 5-2 Evaluation of Straightness of a Planar Surface

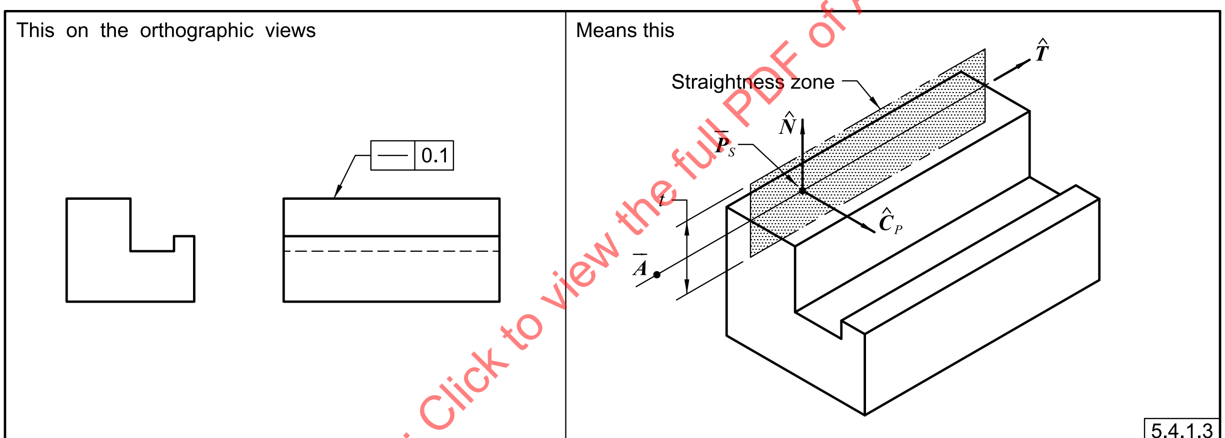
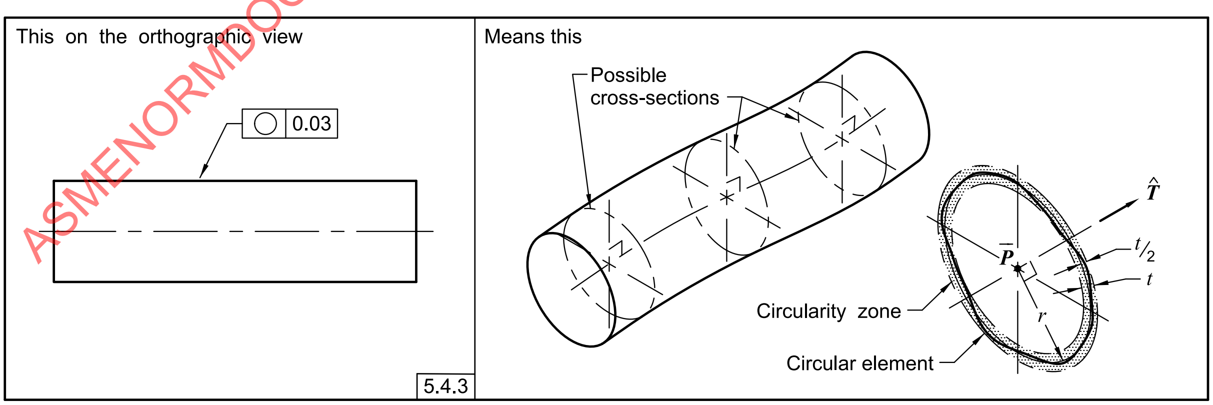


Figure 5-3 Illustration of Circularity Tolerance Zone for a Cylindrical or Conical Feature



Section 6
Tolerances of Orientation

6.1 GENERAL

This Section establishes the principles and methods for mathematical evaluation of ASME Y14.5-2009 dimensioning and tolerancing to control the orientation of features.

6.2 ORIENTATION CONTROL

Per ASME Y14.5-2009

An orientation tolerance controls parallel, perpendicular, and all other angular relationships. Note that an orientation tolerance, when applied to a plane surface, controls flatness to the extent of the orientation tolerance. When the flatness control in the orientation tolerance is not sufficient, a separate flatness tolerance should be considered. An orientation tolerance does not control the location of features. When specifying an orientation tolerance, consideration must be given to the control of orientation already established through other tolerances such as location, runout, and profile controls. [6.2]

6.3 SPECIFYING ORIENTATION TOLERANCES

Per ASME Y14.5-2009

When specifying an orientation tolerance, the considered feature shall be related to one or more datums. Orientation tolerances are constrained only in rotational degrees of freedom relative to the referenced datums; they are not constrained in the translational degrees of freedom. Thus, with orientation tolerances, even in those instances where datum features may constrain all degrees of freedom, the tolerance zone only orients to that datum reference frame. Sufficient datum features should be referenced to constrain the required rotational degrees of the freedom. If the primary datum feature alone does not constrain sufficient degrees of freedom, additional datum features may be specified. [6.4]

An orientation tolerance specifies a zone within which the considered feature, its line elements, its axis, or its center plane must be contained. [6.4.1]

An orientation tolerance specifies one of the following:

(a) a tolerance zone defined by two parallel planes at the specified basic angle from, parallel to, or perpendicular to one or more datum planes or a datum axis, within which the surface or center plane of the considered feature must lie.

(b) a tolerance zone defined by two parallel planes at the specified basic angle from, parallel to, or perpendicular to one or more datum planes or a datum axis, within which the axis of the considered feature must lie.

(c) a cylindrical tolerance zone at the specified basic angle from, parallel to, or perpendicular to one or more datum planes or a datum axis, within which the axis of the considered feature must lie.

(d) a tolerance zone defined by two parallel lines at the specified basic angle from, parallel to, or perpendicular to a datum plane or axis, within which the line element of the surface must lie. [6.4.2]

While the shape of the tolerance zone is defined (a cylinder, a zone bounded by two parallel planes, or a zone bounded by two parallel lines), the extent of the tolerance zone (e.g., the length of the cylinder) must also be considered. There are two cases to be considered:

(a) The extent of the tolerance zone is restricted to control a limited area or length of the surface shown by a chain line drawn parallel to the surface profile dimensioned for length and location.

(b) In all other cases, the extent of the tolerance zone is limited to the actual feature surface. For a feature axis, tangent plane, or center plane the extent is defined by projecting the actual surface points onto the axis, tangent plane, or center plane.

6.4 ORIENTATION TOLERANCE

Per ASME Y14.5-2009

Tolerance zones apply to the full extent of the feature, unless otherwise indicated. Where it is a requirement to control only individual line elements of a surface, a qualifying notation, such as EACH ELEMENT or EACH RADIAL ELEMENT, is added to the drawing. This permits control of individual elements of the surface independently in relation to the datum and does not limit the total surface to an encompassing zone. Although orientation tolerances are only constrained in rotational degrees of freedom relative to the referenced datums, the notation of EACH RADIAL ELEMENT adds a requirement for the tolerance zone(s) to be constrained in location relative to the axis from which the radial elements emanate. Tolerances for individual elements may also be specified using a line profile tolerance. [6.4.3]

Where it is desired to control a tangent plane established by the contacting points of a surface, the tangent plane symbol is added in the feature control frame after the stated tolerance. Where a tangent plane symbol is specified with a geometric tolerance, the flatness of the tolerance feature is not controlled by the geometric tolerance. [6.5]

Mathematically, the equations describing angularity, parallelism, and perpendicularity are identical when generalized in terms of the angle(s) between the tolerance zone and the related datum(s). Accordingly, the generic term *orientation* is used in place of angularity, parallelism, and perpendicularity in the definitions.

An orientation zone is bounded by a pair of parallel planes, a cylindrical surface, or a pair of parallel lines. Each of these cases is defined separately below. If the tolerance value is preceded by the diameter symbol, then the tolerance zone is a cylindrical volume; if the notation EACH ELEMENT or EACH RADIAL ELEMENT appears then the tolerance zone is an area between parallel lines; in all other cases the tolerance zone is a volume between parallel planes by default.

6.4.1 Planar Orientation Tolerance Zone

(a) Definition. An orientation tolerance which is not preceded by the diameter symbol and which does not include the notation EACH ELEMENT or EACH RADIAL ELEMENT specifies that the considered surface, center plane, tangent plane, or axis must lie in a planar orientation zone bounded by two parallel planes separated by the specified tolerance and basically oriented to the primary datum and, if specified, to the secondary datum as well.

A planar orientation zone is a volume consisting of all points $\vec{P}$ satisfying the condition

$$\left|\hat{T}\cdot\left(\vec{P}-\vec{A}\right)\right| \leq \frac{t}{2}$$

where

$\vec{A}$ = any point on the mid-plane of the planar orientation zone

$\hat{T}$ = the direction vector of the planar orientation zone

t = the size of the planar orientation zone (the separation of the parallel planes)

The planar orientation zone is oriented such that, if $\hat{D}_1$ is the direction vector of the primary datum, then

$$\left|\hat{T}\cdot\hat{D}_1\right| = \begin{cases} |\cos \Theta| \text{ for a primary datum axis} \\ |\sin \Theta| \text{ for a primary datum plane} \end{cases}$$

where Θ is the basic angle between the primary datum and the direction vector of the planar orientation zone.

In the following four cases, a secondary datum has no effect:

– perpendicularity of a plane, center plane, or tangent plane to a datum axis

– parallelism of a plane, center plane, or tangent plane to a datum plane

– perpendicularity of an axis to a datum axis with a planar orientation tolerance zone

– parallelism of an axis to a datum plane with a planar orientation tolerance zone

In these cases, the orientation of the planar orientation zone is fully constrained by the primary datum. In the following two cases, if a secondary datum is not specified, then the orientation tolerance may not provide adequate control:

– angularity and parallelism of an axis to a datum axis with a planar orientation tolerance zone

– angularity and perpendicularity of an axis to a datum plane with a planar orientation tolerance zone

When controlling perpendicularity of an axis within a planar orientation tolerance zone with just a primary datum, the planar orientation zone can rotate to contain the axis with an actual value of zero.

If a secondary datum is specified, the planar orientation zone is further restricted to be oriented relative to the direction vector, $\hat{D}_2$, of the secondary datum by

$$\left|\hat{T}'\cdot\hat{D}_2\right| = \begin{cases} |\cos \alpha| \text{ for a secondary datum axis} \\ |\sin \alpha| \text{ for a secondary datum plane} \end{cases}$$

where $\hat{T}'$ is the normalized projection of $\hat{T}$ onto a plane normal to $\hat{D}_1$, and α is the basic angle between the secondary datum and $\hat{T}'$. $\hat{T}'$ is given by

$$\hat{T}' = \frac{\hat{T} - (\hat{T}\cdot\hat{D}_1)\hat{D}_1}{\left|\hat{T} - (\hat{T}\cdot\hat{D}_1)\hat{D}_1\right|}$$

Figure 6-1 shows the relationship of the planar orientation zone direction vector to the primary and secondary datums. Figure 6-2 illustrates the projection of $\hat{T}$ onto the primary datum plane to form $\hat{T}'$.

(b) Conformance. A surface, center plane, tangent plane, or axis S conforms to an orientation tolerance t_0 if all points of S lie within some planar orientation zone as defined above with $t = t_0$. That is, there exist $\hat{T}$ and $\vec{A}$ such that with $t = t_0$, all points of S are within the planar orientation tolerance zone.

NOTE: If the orientation tolerance refers to both a primary datum and a secondary datum, then $\hat{T}$ is fully determined. If the considered feature is a feature of size (cylinder or width), then the orientation tolerance may be applied on a MMC or LMC material condition basis. This increases the width of the planar orientation tolerance zone by the additional tolerance.

(c) Actual Value. The actual value of orientation for S is the smallest orientation tolerance to which S will conform.

6.4.2 Cylindrical Orientation Tolerance Zone

(a) Definition. An orientation tolerance which is preceded by the diameter symbol specifies that the toleranced axis must lie in a cylindrical orientation zone bounded by a cylinder with a diameter equal to the specified tolerance and whose axis is basically oriented to the primary datum and, if specified, to the secondary datum as well.

A cylindrical orientation zone is a volume consisting of all points $\vec{P}$ satisfying the condition

$$\left|\hat{T} \times \left(\vec{P} - \vec{A}\right)\right| \leq \frac{t}{2}$$

where

$\vec{A}$ = any point on the axis of the cylindrical orientation zone

$\hat{T}$ = the direction vector of the axis of the cylindrical orientation zone

t = the diameter of the cylindrical orientation zone

The axis of the cylindrical orientation zone is oriented such that, if $\hat{D}_1$ is the direction vector of the primary datum, then

$$\left|\hat{T}\cdot\hat{D}_1\right| = \begin{cases} |\cos \Theta| & \text{for a primary datum axis} \\ |\sin \Theta| & \text{for a primary datum plane} \end{cases}$$

where Θ is the basic angle between the primary datum and the direction vector of the axis of the cylindrical orientation zone.

In the following cases, a secondary datum has no effect:

– parallelism of an axis to a datum axis, and

– perpendicularity of an axis to a datum plane.

In these cases, the orientation of the cylindrical orientation zone is fully constrained by the primary datum. If a secondary datum is specified, the cylindrical orientation zone is further restricted to be oriented relative to the direction vector, $\hat{D}_2$, of the secondary datum by

$$\left|\hat{T}'\cdot\hat{D}_2\right| = \begin{cases} |\cos \alpha| & \text{for a secondary datum axis} \\ |\sin \alpha| & \text{for a secondary datum plane} \end{cases}$$

where $\hat{T}'$ is the normalized projection of $\hat{T}$ onto a plane normal to $\hat{D}_1$, and α is the basic angle between the secondary datum and $\hat{T}'$. $\hat{T}'$ is given by

$$\hat{T}' = \frac{\hat{T} - (\hat{T}\cdot\hat{D}_1)\hat{D}_1}{\left|\hat{T} - (\hat{T}\cdot\hat{D}_1)\hat{D}_1\right|}$$

Figure 6-3 illustrates a cylindrical orientation zone.

(b) Conformance. An axis S conforms to an orientation tolerance t_0 if all points of S lie within some cylindrical orientation zone as defined above with $t = t_0$. That is, there exists $\hat{T}$ and $\vec{A}$ such that with $t = t_0$, all points of S are within the cylindrical orientation tolerance zone.

NOTE: If the orientation tolerance refers to both a primary datum and a secondary datum, then $\hat{T}$ is fully determined. If the orientation tolerance is applied to a cylinder, then a MMC or LMC material condition may be applied. This increases the diameter of the cylindrical orientation tolerance zone by the additional tolerance.

(c) Actual Value. The actual value of orientation for S is the smallest orientation tolerance to which S will conform.

6.4.3 Linear Orientation Tolerance Zone

(a) Definition. An orientation tolerance which includes the notation EACH ELEMENT or EACH RADIAL ELEMENT specifies that each line element of the toleranced surface must lie in a linear orientation zone bounded by two parallel lines which are

(1) in the cutting plane defining the line element

(2) separated by the specified tolerance

(3) basically oriented to the primary datum and, if specified, to the secondary datum as well.

For a surface point $\vec{P_s}$, a linear orientation zone is an area consisting of all points $\vec{P}$ in a cutting plane of direction vector $\hat{C}_p$ that contains $\vec{P_s}$. The points $\vec{P}$ satisfy the following conditions:

$$\hat{C}_p\cdot\left(\vec{P} - \vec{P_s}\right) = 0$$

and

$$\left|\hat{T} \times \left(\vec{P} \times \vec{A}\right)\right| \leq \frac{t}{2}$$

where

$\vec{A}$ = any point on the center line of the linear orientation zone

$\hat{C}_p$ = the normal to the cutting plane and basically oriented to the datum reference frame

$\vec{P_s}$ = a point on S

$\hat{T}$ = the direction vector of the center line of the linear orientation zone

t = the size of the linear orientation zone (the separation between the parallel lines)

The position vector $\vec{A}$, which locates the center line of the linear orientation zone, also locates the cutting plane through the following constraint:

$$\hat{C}_p\cdot\left(\vec{P_s} - \vec{A}\right) = 0$$

In some cases, if a secondary datum is not specified then the orientation tolerance may not provide adequate control: angularity of a surface line element to a datum axis or a datum plane. If a secondary datum axis is specified, and the toleranced feature in its nominal condition is rotationally symmetric about that datum axis, then the cutting planes are further restricted to contain the datum axis as follows:

$$\hat{C}_p \cdot \left(\vec{P}_s - \vec{B}\right) = 0$$

where $\vec{B}$ is a position vector that locates the datum axis. Otherwise, the cutting planes are required to be parallel to one another.

The direction vector of the center line of the linear orientation zone, $\hat{T}$, is constrained to lie in the cutting plane by

$$\hat{C}_p \cdot \hat{T} = 0$$

The center line of the linear orientation zone is oriented such that, if $\hat{D}_1$ is the direction vector of the primary datum, then

$$\left|\hat{T} \cdot \hat{D}_1\right| = \begin{cases} |\cos \Theta| \text{ for a primary datum axis} \\ |\sin \Theta| \text{ for a primary datum plane} \end{cases}$$

where Θ is the basic angle between the primary datum and the direction vector of the linear orientation zone.

NOTE: If a secondary datum is not specified, at least one of $\hat{T}$ and $\hat{D}_1$ will not be defined, and so the actual value will not be defined.

Figure 6-4 illustrates a linear orientation zone bounded by parallel lines on a cutting plane for the controlled surface.

(b) Conformance. A surface, center plane, or tangent plane S conforms to an orientation tolerance t_0 for a cutting plane $\hat{C}_p$ if all points of the intersection of S with $\hat{C}_p$ lie within some linear orientation zone as defined above with $t = t_0$. That is, there exist $\hat{T}$ and $\vec{A}$ such that with $t = t_0$, all points of S are within the linear orientation tolerance zone.

A surface S conforms to the orientation tolerance t_0 if it conforms simultaneously for all surface points and cutting planes $\hat{C}_p$.

NOTE: If the orientation tolerance refers to both a primary datum and a secondary datum, then $\hat{T}$ is fully determined.

(c) Actual Value. The actual value of orientation for S is the smallest orientation tolerance to which S will conform.

Figure 6-1 Planar Orientation Zone With Primary and Secondary Datum Planes Specified

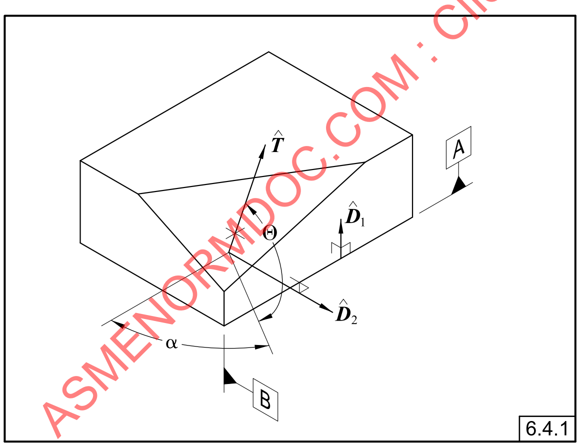


Figure 6-2 Projection of Tolerance Vector Onto Primary Datum Plane

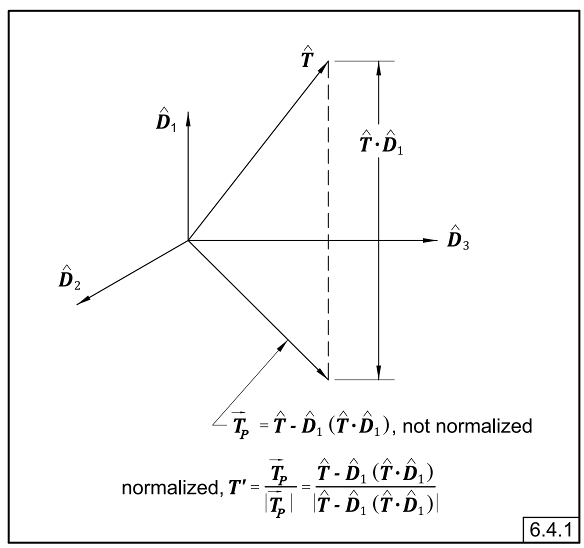


Figure 6-3 Cylindrical Orientation Zone With Respect to a Primary Datum Plane

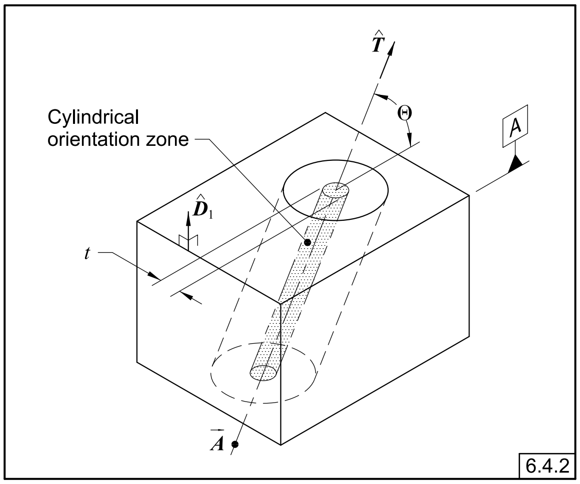
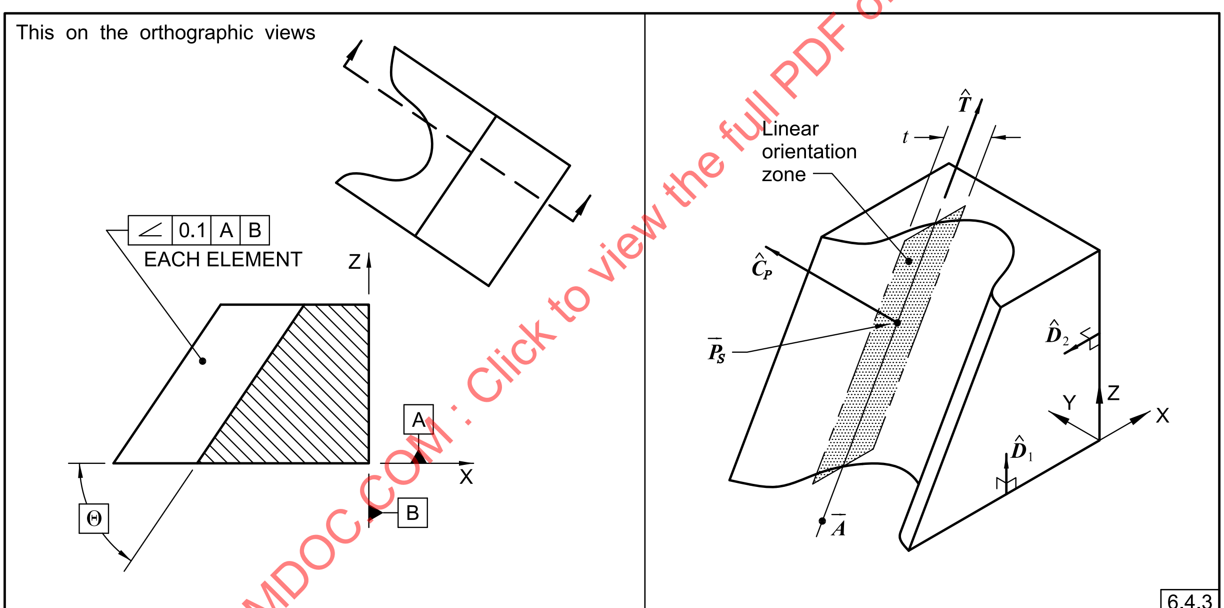


Figure 6-4 Linear Orientation Zone Bounded by Parallel Lines



Section 7
Tolerances of Location

7.1 GENERAL

This Section establishes the principles of tolerances of location; included are position, concentricity, and symmetry used to control the following relationships:

(a) center distance between (features of size, such as) holes, slots, bosses, and tabs

(b) location of features of size [such as in (a) above] as a group with respect to datum reference frames

(c) coaxiality and coplanarity of features of size

(d) concentricity or symmetry of features of size — center distances of correspondingly-located feature elements equally disposed about a datum axis or plane

7.1.1 Material Condition Basis

Position tolerances are applied on an MMC, RFS, or LMC basis. A position tolerance may be explained either in terms of the surface method of the actual feature or in terms of size and the resolved geometry (center point, axis, or center plane) of the applicable (mating or minimum material) actual envelope. These two interpretations will be called the "surface interpretation" and the "resolved geometry interpretation," respectively. (See subsection 7.2 and the following for the precise definitions of position tolerancing interpretations.) These interpretations are not equivalent. They differ in part because the resolved geometry interpretation relies on an assumption that the feature is of perfect form and in part because the derivation of the surface interpretation assumes perfect orientation.

Two examples will illustrate these interpretations. Consider the illustration in Figure 7-1. The hole shown in the figure is controlled by a zero position tolerance at MMC. The theoretical boundary (virtual condition) has a diameter equal to the MMC diameter of the hole. The actual hole was manufactured with poor form, but is within the limits of size (see para. 2.3.1). The hole does not violate the theoretical boundary (virtual condition), and would be acceptable per the surface interpretation. The resolved geometry (the axis of the hole) is further away from true position than allowed by the combined effects of the position tolerance (zero) and the bonus tolerance resulting from the unrelated actual mating envelope of the hole. The hole would not be acceptable per the resolved geometry interpretation.

Figure 7-2 shows the converse situation. The shaft shown in the figure is controlled by a position tolerance t_0 at MMC. The shaft was manufactured with perfect form. If the radius of the shaft is r_{AM} and the MMC radius is r_{MMC}, the radius of the tolerance zone for the axis is $r_{MMC} - r_{AM} + t_0/2$. If the height of the shaft is h, and the axis of the actual shaft is tilted to an extreme orientation within the tolerance zone, a simple geometric analysis shows that point $\vec{\boldsymbol{P}}$ lies outside the theoretical boundary (virtual condition) by a distance

$$r_{AM}\left[\sqrt{1 + [(t + 2(r_{MMC} - r_{AM}))/h]^2} - 1\right]$$

The feature illustrated in Figure 7-2 is acceptable per the resolved geometry interpretation but unacceptable per the surface interpretation.

Throughout most of this Section, both a surface interpretation and a resolved geometry interpretation are supplied. In a few cases (e.g., projected tolerance zones) only a surface interpretation is provided. Whenever the two interpretations do not produce equivalent results, the surface interpretation shall take precedence.

7.1.2 Patterns of Features

For the purposes of this Standard, all tolerances of location are considered to apply to patterns of features, where a pattern may consist of only a single feature. The control of the location of the pattern as a group is called the pattern-locating tolerance zone framework (PLTZF). When the pattern consists of two or more features, there is the possibility, through the use of composite tolerancing, to control the relative location of features within the pattern. This is done by specifying a secondary location tolerance, called the feature-relating tolerance zone framework (FRTZF), in conjunction with the PLTZF. There may be more than one FRTZF for a pattern. All features within a single pattern are controlled simultaneously. That is, all features must be evaluated with respect to a single datum reference frame from the candidate datum reference frame set for the control.

7.2 POSITION TOLERANCING

This subsection presents a general explanation of position tolerancing for features of size. A position tolerance can be explained in terms of a zone within which the resolved geometry (center point, axis, or center plane) of a feature of size is permitted to vary from true (theoretically exact) position. Basic dimensions establish the theoretical true position from specified datum features and between interrelated features. A position tolerance can be explained in terms of a surface boundary.

Throughout this subsection, whenever the true position is understood from context, the notation $r\left(\vec{P}\right)$ will denote the distance from a point $\vec{P}$ to the true position. For spheres, $r\left(\vec{P}\right)$ is the distance to the true position center point. For cylinders, $r\left(\vec{P}\right)$ is the distance between $\vec{P}$ and the true position axis. For parallel plane features, $r\left(\vec{P}\right)$ is the distance between $\vec{P}$ and the true position center plane. These definitions should also be understood to be for a particular choice of datum reference frame from the candidate datum reference frame set. Throughout this Section, all spherical and cylindrical sizes are in terms of radius unless otherwise specified. All tolerance values are assumed to be diameters for spheres and cylinders, and full widths for parallel planes, in accord with common practice.

7.2.1 In Terms of the Surface of a Feature

(a) Definition. For a pattern of features of size, a position tolerance specifies that the surface of each actual feature must not violate the boundary of a corresponding position tolerance zone. Each boundary is a sphere, cylinder, or pair of parallel planes of size equal to the collective effect of the limits of size, material condition basis, and applicable position tolerance. Each boundary is located and oriented by the basic dimensions of the pattern and datum(s) if specified. Each position tolerance zone is a volume defined by all points $\vec{P}$ that satisfy the appropriate equation from Table 7-1, where b is a position tolerance zone size parameter (radius or half-width).

Figure 7-3 illustrates the tolerance zone for a cylindrical hole at MMC or RFS, or a shaft at LMC. The tolerance zone is a cylindrical volume.

Figure 7-4 illustrates the tolerance zone for a tab at MMC or RFS, or a slot at LMC. The tolerance zone is a pair of parallel planar volumes.

(b) Conformance. A feature conforms to a position tolerance t_0 at a specified material condition basis if all points of the feature lie outside some position zone as defined above with b determined by the appropriate value from Table 7-2.

The surface must conform to the applicable size limits. In the case of an internal feature at MMC or RFS or an external feature at LMC, there is a further condition that the feature must surround the tolerance zone.

For MMC or LMC material condition basis, the boundary defined by $r\left(\vec{P}\right) = b$, with b as given here, is the theoretical boundary (virtual condition).

(c) Actual Value. The actual value of position deviation is the smallest value of t_0 to which the feature conforms.

NOTE: For LMC and MMC controls the actual value of deviation can be negative. A negative value can be interpreted as the unused portion of the bonus tolerance resulting from the departure of the feature from the applicable limit of size.

7.2.2 In Terms of the Resolved Geometry of a Feature

(a) Definition. For a pattern of features of size, a position tolerance specifies that the resolved geometry (center point, axis, or center plane, as applicable) of each unrelated actual mating envelope (for features at MMC or RFS) or unrelated actual minimum material envelope (for features at LMC) must lie within a corresponding position tolerance zone. Each tolerance zone is bounded by a sphere, cylinder, or pair of parallel planes of size equal to the total allowable tolerance for the corresponding feature. Each tolerance zone is located and oriented by the basic dimensions of the pattern relative to a datum reference frame. A position tolerance zone is a spherical, cylindrical, or parallel-plane volume defined by all points $\vec{P}$ that satisfy the equation $r\left(\vec{P}\right) \leq b$, where b is the radius or half-width of the tolerance zone.

Figure 7-5 illustrates the tolerance zone for holes at MMC and RFS and for shafts at LMC. The figure shows the position of a point on the axis of the actual mating envelope that is outside the tolerance zone. A similar figure for holes at LMC or shafts at MMC or RFS would show the actual mating envelope surrounding the feature surface. The feature axis extends for the full length of the feature.

(b) Conformance. A feature conforms to a position tolerance t_0 at a specified material condition basis if all points of the resolved geometry of the applicable envelope (as determined by the material condition basis) lie within some position tolerance zone as defined above with b determined by the appropriate formula from Table 7-3. Furthermore, the surface must conform to the applicable size limits.

(c) Actual Value. The position deviation of a feature is the diameter of the smallest zone (smallest value of b) which contains the center point or all points on the axis or center plane (within the extent of the feature) of the applicable actual mating envelope of the feature.

7.3 PROJECTED TOLERANCE ZONE

(a) Definition. For a cylindrical or parallel-plane feature, a projected tolerance specifies that a volume, called a verifying volume, with a boundary of perfect

form, called a verifying boundary, can be defined such that the following two conditions hold. First, the axis or center plane of the verifying boundary is contained within a projected position tolerance zone, itself a boundary of perfect form extending outward from the feature by the specified projection length. Second, the surface of the feature does not violate the verifying volume.

A projected position tolerance zone is a cylindrical or parallel-plane volume defined by all points $\vec{P}$ that satisfy the equation $r\left(\vec{P}\right) \le b$, where b is the radius or half-width of the tolerance zone. A verifying volume is a cylindrical or parallel-plane volume defined by all points $\vec{P}$ that satisfy the appropriate equation from Table 7-4, where w is a size parameter for the verifying volume.

Figure 7-6 illustrates a typical case. The projected tolerance zone is positioned and oriented by the choice of datum reference frame. A plane perpendicular to the true position axis is located to contact the part surface that defines the end of the cylindrical feature. The height of the tolerance zone is the specified projection length and starts at the point where the true position axis intersects the contacting plane. The verifying volume is shown for a hole at MMC or RFS. (A similar picture would apply for a shaft at LMC. For a shaft at MMC or RFS, or a hole at LMC, the verifying envelope would surround the feature.)

(b) Conformance. A feature conforms to a position tolerance t_0, projected a distance h, and at a specified material condition basis, if there exists at least one verifying volume for which the following conditions hold. All points of the feature lie outside the verifying volume as defined above with w determined from the material basis as follows:

(1) for MMC, $w = r_{\mathrm{MMC}}$
(2) for RFS, $w = r_{\mathrm{AM}}$
(3) for LMC, $w = r_{\mathrm{LMC}}$

The verifying envelope satisfies $r\left(\vec{P}\right) \le t_0/2$ for all points $\vec{P}$ on the resolved geometry starting at the intersection of the resolved geometry with the contacting plane and ending at the intersection of the resolved geometry with a second plane parallel to the contacting plane and separated from it by a distance h.

NOTE: For RFS features, this definition can also be considered the resolved geometry interpretation. No resolved geometry interpretation is provided for MMC or LMC tolerances.

(c) Actual Value. The position deviation of a feature is the size of the smallest projected zone such that the resolved geometry of the actual mating envelope lies within the zone for the full projection height.

7.4 CONICAL TOLERANCE ZONE

A conical position tolerance zone is specified by different position tolerance values at each end of a cylindrical feature. A conical tolerance can be interpreted either in terms of the surface of the feature or in terms of the axis of the feature.

7.4.1 In Terms of the Surface of the Feature

(a) Definition. For a pattern of cylindrical features, a position control tighter at one end of the features than the other specifies that the surface of each actual feature must not violate a corresponding perfect-form conical boundary. This boundary is a frustum of height and diameters equal to the collective effects of the limits of size, material condition basis, and applicable position tolerances at each end of the feature. The boundary is located and oriented by the basic dimensions of the feature. A position tolerance zone is a conical volume defined by all points $\vec{P}$ that satisfy the appropriate equation from Table 7-5, where $b(\vec{P})$ is the radius of the tolerance zone at height $\vec{P}$. The radius $b(\vec{P})$ is related to the position tolerance zone size parameters r_1 and r_2 by

$$b(\vec{P}) = r_1\left(1 - \gamma(\vec{P})\right) + r_2\gamma(\vec{P})$$

where

$$\gamma(\vec{P}) = \frac{(\vec{P} - \vec{P}_1)\cdot(\vec{P}_2 - \vec{P}_1)}{\left|\vec{P}_2 - \vec{P}_1\right|^2}$$

is the position of $\vec{P}$ along the axis between $\vec{P}_1$ and $\vec{P}_2$, scaled so that $\gamma(\vec{P}_1) = 0$ and $\gamma(\vec{P}_2) = 1$.

Figure 7-7 illustrates the tolerance zone for holes at MMC and RFS. Shafts at LMC would have a similar figure. A similar figure for holes at LMC or shafts at MMC or RFS would show the envelope surrounding the feature surface. The tolerance zone axis extends between points $\vec{P}_1$ and $\vec{P}_2$, which are the intersection of the true position axis with two planes, one at each end of the basic feature, at nominal distance and nominally located and oriented relative to the datum reference frame.

(b) Conformance. A cylindrical feature conforms to position tolerances t_1 and t_2 at a specified material condition basis if all points of the feature lie outside the position tolerance zone as defined above, with r_i ($i \in \{1,2\}$) determined according to Table 7-6. The surface must also conform to the applicable size limits. In the case of a hole, there is a further condition that the hole must surround the tolerance zone.

(c) Actual Value. No definition for actual value of position deviation is provided for the surface interpretation. Refer to para. 7.4.2 to the resolved geometry (axis) interpretation for a definition of actual value.

7.4.2 In Terms of the Resolved Geometry (Axis) of the Feature

(a) Definition. For the axes of cylindrical features within a pattern, a position tolerance tighter at one end specifies that the axes of the actual mating envelopes (for features at MMC or RFS) or of the actual minimum material envelopes (for features at LMC) must lie within corresponding position tolerance zones. Each of these tolerance zones is bounded by a frustum of height and diameters equal to the collective effects of the limits of size, material condition basis, and applicable position tolerances at each end of the feature. The axis of the frustum is located and oriented by the basic dimensions of the feature. The frustum is located along the axis by the nominal surfaces bounding the feature. The position tolerance zone is a conical volume defined by all points $\vec{P}$ that satisfy the equation $r\left(\vec{P}\right) \leq b\left(\vec{P}\right)$, where $b\left(\vec{P}\right)$ is the radius of the tolerance zone at the height along the axis of $\vec{P}$. (See the surface interpretation, para. 7.4.1, for details.)

Figure 7-8 illustrates the axis definition for holes. The tolerance zone axis extends between points $\vec{P}_1$ and $\vec{P}_2$, which are the intersection of the true position axis with the nominal surfaces bounding the feature.

(b) Conformance. A cylindrical feature conforms to position tolerances t_1 and t_2 at a specified material condition basis if all points on the axis of the applicable envelope (as determined by the material condition basis) lie within the position tolerance zone as defined above, with r_i ($i \in \{1,2\}$) determined by the appropriate formula from Table 7-7. Furthermore, the surface must conform to the applicable size limits.

(c) Actual Value. A cylindrical feature controlled by a conical tolerance zone has two actual values for position deviation, one at each end of the feature. The actual value at each end is the smallest diameter circle that contains the axis of the actual mating envelope at that end. Each circle is in the plane perpendicular to the true position axis at the end point of the feature axis, and is centered on the true position axis. In the case that the actual mating envelope can rock, it may be possible to decrease the actual value of position deviation at one end at the expense of the deviation at the other end. No rule is defined for selecting among possible pairs of actual values.

7.5 BIDIRECTIONAL POSITION TOLERANCING

A bidirectional position tolerance zone for a cylindrical feature is specified by different position tolerance values in different directions perpendicular to the basic feature axis. Bidirectional position tolerancing results in two distinct tolerance zones for locating each cylindrical feature. Each tolerance zone is considered separately in the following. As with other tolerances, however, rules for simultaneous or separate requirements apply to the components of a bidirectional position tolerance. (See para. 4.7.10.) Bidirectional position tolerancing may be applied in either a rectangular or a polar (cylindrical) coordinate system. Rectangular bidirectional tolerancing can be explained in terms of either the surface or the axis of the feature. A resolved geometry (axis) interpretation only is provided for polar bidirectional tolerancing.

7.5.1 In Terms of the Surface of the Feature

This paragraph establishes the surface interpretation of bidirectional position tolerancing when applied in a rectangular coordinate system.

(a) Definition. For a pattern of cylindrical features, each bidirectional position tolerance specifies that each surface must not violate a tolerance boundary. For holes at MMC or RFS and shafts at LMC, each tolerance boundary is a cylinder of diameter equal to the collective effects of the limits of size, material condition basis, and applicable position tolerance. Each boundary is located and oriented, by the basic dimensions of the pattern relative to the specified datum reference frame and by the applicable direction of tolerance control, such that the axis of each boundary lies in the plane containing the true position axis of the corresponding feature and normal to the direction in which the tolerance applies. The orientation and position of the boundary axis within this plane is unconstrained.

For holes at LMC and shafts at MMC or RFS, each tolerance boundary is a pair of parallel planes separated by a distance equal to the collective effects of the limits of size, material condition basis, and applicable position tolerance. The center plane of each boundary is that plane containing the axis of the corresponding feature and normal to the direction in which the tolerance applies.

A position tolerance zone is a volume defined by all points $\vec{P}$ that satisfy the appropriate equation from Table 7-8, where b is a position tolerance zone size parameter (radius or half-width).

(b) Conformance. A cylindrical feature conforms to a bidirectional position tolerance t_0 at a specified material condition basis if all points of the feature lie outside some position tolerance as defined above with b determined by the appropriate value from Table 7-9.

Figure 7-9 shows an example of bidirectional tolerancing of a hole at MMC. Each callout creates its own cylindrical position tolerance zone. The tolerance zone corresponding to the 0.4 mm tolerance, shown in the bottom left, is free to be located and oriented only in the plane indicated by the vertical dashed line. Similarly, the tolerance zone corresponding to the 0.2 mm tolerance, shown in the bottom right, is only free to be located and oriented left-to-right in the view shown. Each of these planes of motion are determined by the basic dimensions from the indicated datums.

A similar example is illustrated for shafts at MMC in Figure 7-10. In this case, each callout creates a tolerance zone bounded by parallel planes. The tolerance zone corresponding to the 0.4 mm tolerance is bounded by the vertical planes separated by 16.6 mm. The tolerance zone corresponding to the 0.2 mm tolerance is bounded by the horizontal planes separated by 16.4 mm.

(c) Actual Value. No definition for actual value of bidirectional position deviation is provided in terms of the surface of the feature. Refer to para. 7.5.2 to the resolved geometry (axis) interpretation for a definition of actual value.

7.5.2 In Terms of the Resolved Geometry (Axis) of the Feature

This paragraph establishes the resolved geometry (axis) interpretation of bidirectional position tolerancing when applied in a rectangular coordinate system.

(a) Definition. For axes of cylindrical features within a pattern, bidirectional position tolerances specify that the axis of each unrelated actual mating envelope (for features at MMC or RFS) or minimum material envelope (for features at LMC) must lie within two corresponding position tolerance zones. Each position tolerance zone is bounded by two parallel planes separated by a distance equal to the total allowable tolerance for the corresponding feature, including any effects of feature size. Each position tolerance zone is located and oriented by the basic dimensions of the pattern relative to the specified datum reference frame. A bidirectional position tolerance zone is a (slab) volume defined by all points $\vec{P}$ that satisfy the equation $r\left(\vec{P}\right) \leq b$, where b is half the thickness of the tolerance zone.

(b) Conformance. A cylindrical feature conforms to a position tolerance t_0 at a specified material condition basis if all points on the axis of the applicable envelope (as determined by the material condition basis) lie within the position tolerance zone as defined above with b determined by the appropriate formula from Table 7-10. Furthermore, the surface must conform to the applicable size limits.

(c) Actual Value. The position deviation of a feature is the thickness of the smallest tolerance zone to which the axis conforms.

NOTE: There is a distinct actual value for each tolerance callout in a bidirectional position tolerance.

7.5.3 Polar Bidirectional Tolerancing in Terms of the Resolved Geometry (Axis) of the Feature

This paragraph establishes the resolved geometry (axis) interpretation of bidirectional position tolerancing when applied in a cylindrical coordinate system. (While the term "polar" is used in ASME Y14.5-2009, and used herein for consistency, a cylindrical coordinate system is being used. The tolerances are specified in the plane normal to the axis of the cylindrical coordinate system.)

(a) Definition. For axes of cylindrical features within a pattern, polar bidirectional position tolerances specify that the axes of the actual mating envelopes (for features at MMC or RFS) or of the minimum material envelopes (for features at LMC) must lie within corresponding position tolerance zones. Each tolerance zone is bounded radially by two concentric cylindrical arcs and tangentially by two planes symmetrically disposed about the true position of the feature and oriented at the basic polar angle of the feature. The plane separation and the difference in cylindrical arc radii are each equal to the total allowable tolerance for the corresponding feature, including any effects of feature size. Each tolerance zone is located and oriented by the basic dimensions of the pattern. A polar bidirectional position tolerance zone is a (cylindrical shell) volume defined by all points $\vec{P}$ that satisfy the following two equations:

$$\left|\rho_{\vec{P}} - \rho_0\right| < b_r$$

and

$$\left|\left(\vec{P} - \vec{A}\right)\cdot\hat{N}_t\right| \leq b_t$$

where

$\vec{A}$ = a point on the true position axis of the feature

b_r = the tolerance zone size parameter for the cylindrical boundaries of the tolerance zone, equal in value to half the difference in radii of the boundaries

b_t = the tolerance zone size parameter for the planar boundaries of the tolerance zone, equal in value to half of the distance between the boundaries

$\hat{N}_t$ = the direction vector of the plane containing the axis of the polar (cylindrical) coordinate system and the true position axis of the feature

$\rho_{\vec{P}}$ = the distance of $\vec{P}$ from the axis of the polar (cylindrical) coordinate system

ρ_0 = the distance of the true position axis from the axis of the polar (cylindrical) coordinate system

The relationship between these quantities is illustrated in Figure 7-11.

(b) Conformance. A cylindrical feature conforms to a polar, bidirectional position tolerance with radial component t_r and tangential component t_t, each applied at a specified material condition basis, if all points on the axis of the applicable envelope (as determined by the material condition basis) lie within the position tolerance zone as defined above with b_r and b_t determined by the appropriate formula from Table 7-11, with $t = t_r$ and $t = t_t$, respectively. Furthermore, the surface must conform to the applicable size limits.

(c) Actual Value. As with rectangular, bidirectional position tolerancing, two actual values of position deviation are defined. The actual value of position deviation in either the radial or tangential direction is the thickness of the smallest tolerance zone to which the applicable axis conforms.

7.6 POSITION TOLERANCING AT MMC FOR BOUNDARIES OF ELONGATED HOLES

An elongated hole is an internal feature consisting of two parallel, opposed, planar faces terminated by cylindrical end caps, tangent to the planar faces, with axes inside the hole. For purposes of position tolerancing, an elongated hole is considered a feature of size, characterized by two size parameters, its length and width. Such tolerancing is always considered to be bidirectional in nature, even if a single tolerance value is applied. Only a surface interpretation is provided.

(a) Definition. For a pattern of elongated holes, a position tolerance at MMC specifies that the surface of each actual hole must not violate the boundary of a corresponding tolerance zone. Each boundary is a right cylinder with an elongated cross section of perfect form as shown in Figure 7-12. Each boundary is located and oriented by the basic dimensions of the pattern relative to the specified datum reference frame. Each position tolerance zone is the volume interior to the corresponding boundary (the shaded area in Figure 7-12). The boundary size is characterized by two size parameters, ℓ and w, representing, respectively, the half-length and half-width of the tolerance zone.

(b) Conformance. A position tolerance for an elongated hole specifies two values

(1) t_w, controlling position deviation in the direction of the hole width

(2) t_ℓ, controlling position deviation along the length of the hole

An elongated hole conforms to position tolerances t_w and t_ℓ if all points of the hole surface lie outside the position tolerance zone as defined above, with $w = w_{MMC} - t_w/2$ and $\ell = \ell_{MMC} - t_\ell/2$, where w_{MMC} is the MMC width of the elongated hole and ℓ_{MMC} is the MMC length of the elongated hole.

Furthermore, the hole must surround the tolerance zone and must conform to the limits of size. An elongated hole conforms to the limits of size if there exist two right, elongated-hole cylinders (unconstrained in location or orientation), such that the following conditions hold. One cylinder, with w and ℓ equal to the MMC limits of size, is surrounded by the hole surface. The other cylinder, with w and ℓ equal to the LMC limits of size, surrounds the hole surface.

(c) Actual Value. No actual value of position deviation for elongated holes is defined.

7.7 CONCENTRICITY AND SYMMETRY

This subsection provides definitions of concentricity and symmetry tolerances that control concentricity and symmetry of features. Concentricity and symmetry controls are similar concepts and are treated together in this Section. Concentricity is that condition where the median points (centroids) of all diametrically opposed elements of a figure of revolution (or correspondingly located elements of two or more radially disposed features) are congruent with a datum axis or center point. Symmetry is that condition where one or more features is equally disposed about a datum plane. A symmetry tolerance is used for the mathematical concept of symmetry about a plane and a concentricity tolerance is used for the mathematical concept of symmetry about a point or symmetry about an axis. Concentricity and symmetry controls are applied to features on an RFS basis only. Datum references must also be RMB.

(a) Definition. A concentricity or symmetry tolerance specifies that the centroid of corresponding point elements on the surfaces of the actual features must lie in the symmetry tolerance zone. The tolerance zone is bounded by a sphere, cylinder, or pair of parallel planes of size equal to the total allowable tolerance for the features. The tolerance zone is located and oriented by the basic dimensions of the feature(s) relative to the specified datum reference frame. The tolerance zone is a spherical, cylindrical, or parallel-plane volume defined by all points $\vec{\boldsymbol{P}}$ that satisfy the equation $r\left(\vec{\boldsymbol{P}}\right) \leq b$, where b is the radius or half-width of the tolerance zone.

Corresponding point elements are obtained by intersecting a pattern of symmetry rays with the actual feature. The rays of symmetry are determined per Table 7-12. If the feature is symmetric about a plane, a two-fold symmetry pattern is always used. For point and axis symmetry, the symmetry pattern is constructed using the lowest order of symmetry of the basic feature. One consequence of this is that surfaces of revolution use two-fold patterns of symmetry rays about the axis or center of symmetry. The feature elements are located at the intersection of the symmetry rays and the actual feature surface.

This principle is illustrated in Figure 7-13. A feature that has basic three-fold symmetry about a point or (as shown in the figure) an axis results in a three-fold symmetry for the symmetry rays. If the symmetry of the feature is sixfold, however, the symmetry rays are arranged in a two-fold pattern.

(b) Conformance. A feature conforms to its symmetry or concentricity tolerance if the centroids of corresponding points of intersection of the rays with the feature all lie within the tolerance zone as defined above with $b = t_0/2$.

(c) Actual Value. The actual value of concentricity or symmetry deviation is the smallest tolerance value to which the feature will conform.

Figure 7-1 First Illustration of the Difference Between Surface and Resolved Geometry Interpretations of Position Tolerancing

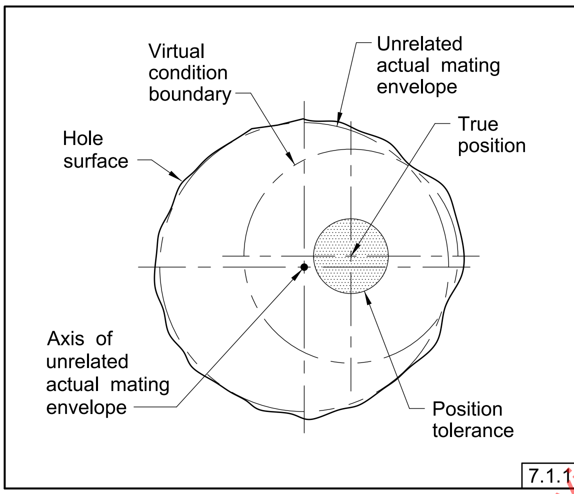


Figure 7-2 Second Illustration of the Difference Between Surface and Resolved Geometry Interpretations of Position Tolerancing

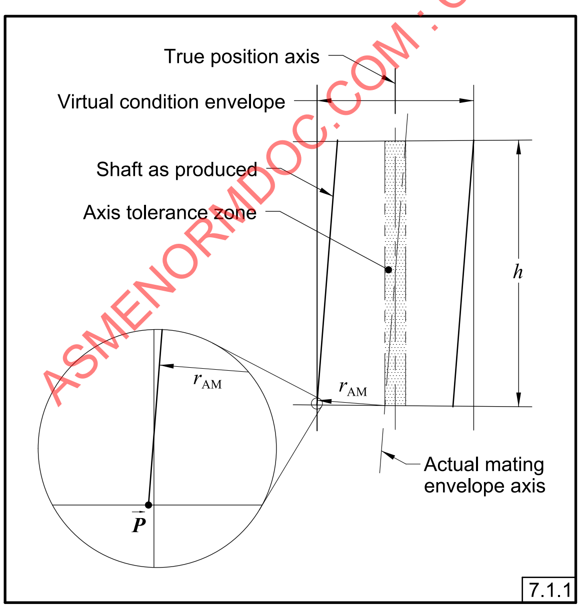


Table 7-1 Definition of Position Tolerance Zone — Surface Interpretation

		Material Condition Basis	
		MMC or RFS	LMC
Feature Type	Internal	$r(\vec{P}) < b$	$r(\vec{P}) > b$
	External	$r(\vec{P}) > b$	$r(\vec{P}) < b$

Figure 7-3 Tolerance Zone and Conformance: Holes at MMC or RFS, Shafts at LMC — Surface Interpretation

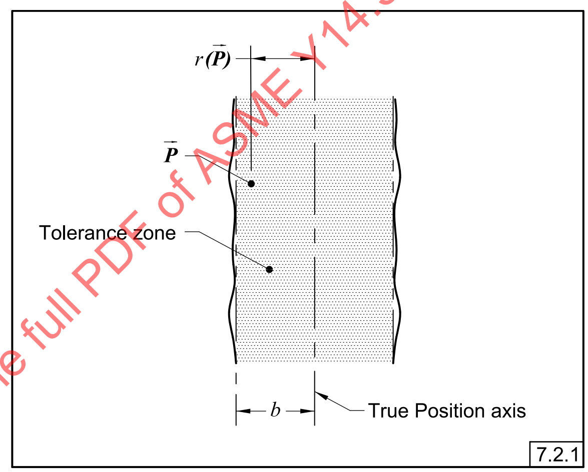


Figure 7-4 Tolerance Zone and Conformance: Tabs at MMC or RFS, Slots at LMC — Surface Interpretation

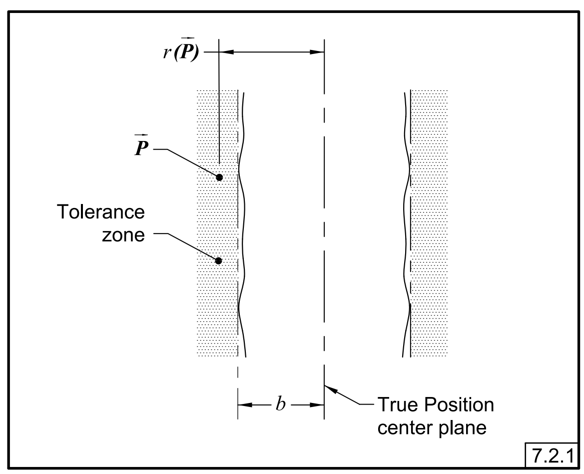


Table 7-2 Size of Position Tolerance Zone — Surface Interpretation

		Material Condition Basis		
	b	**MMC**	**RFS**	**LMC**
Feature Type	**Internal**	$r_{MMC} - \frac{t_0}{2}$	$r_{AM} - \frac{t_0}{2}$	$r_{LMC} + \frac{t_0}{2}$
	External	$r_{MMC} + \frac{t_0}{2}$	$r_{AM} + \frac{t_0}{2}$	$r_{LMC} - \frac{t_0}{2}$

Figure 7-5 Tolerance Zone and Conformance: Holes at MMC or RFS, Shafts at LMC — Resolved Geometry Interpretation

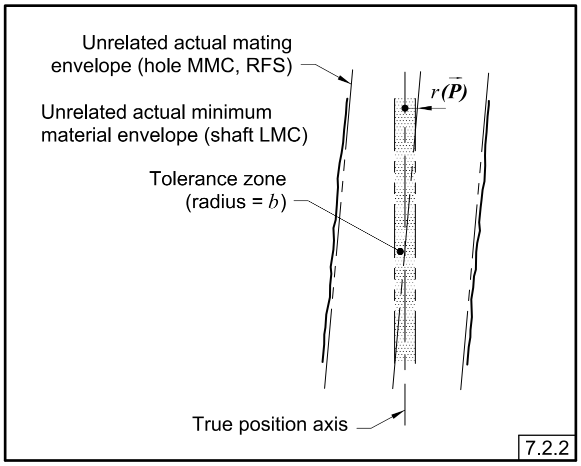


Table 7-3 Size of Position Tolerance Zone — Resolved Geometry Interpretation

		Material Condition Basis		
	b	**MMC**	**RFS**	**LMC**
Feature Type	**Internal**	$\frac{t_0}{2} + (r_{AM} - r_{MMC})$	$\frac{t_0}{2}$	$\frac{t_0}{2} + (r_{LMC} - r_{AMM})$
	External	$\frac{t_0}{2} + (r_{MMC} - r_{AM})$	$\frac{t_0}{2}$	$\frac{t_0}{2} + (r_{AMM} - r_{LMC})$

Table 7-4 Definition of Verifying Volume for Projected Tolerance Zone

		Material Condition Basis	
		MMC or RFS	**LMC**
Feature Type	**Internal**	$r\left(\vec{P}\right) < w$	$r\left(\vec{P}\right) > w$
	External	$r\left(\vec{P}\right) > w$	$r\left(\vec{P}\right) < w$

Figure 7-6 Projected Tolerance Zone for a Hole

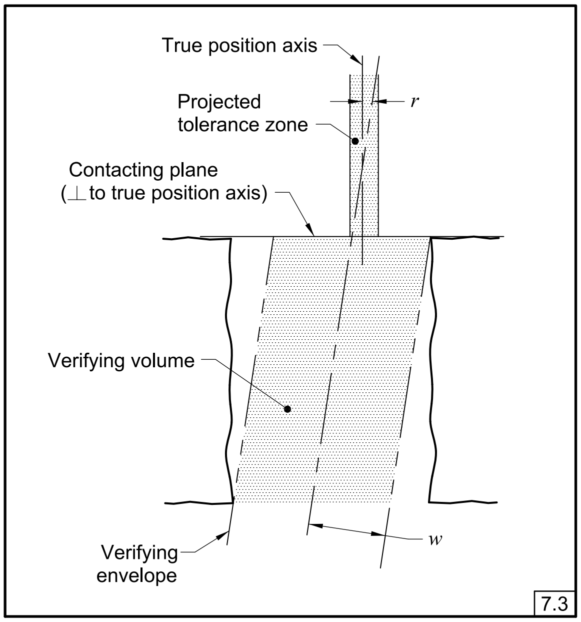


Figure 7-7 Surface Interpretation of Conical Tolerance Zone for Holes at MMC or RFS

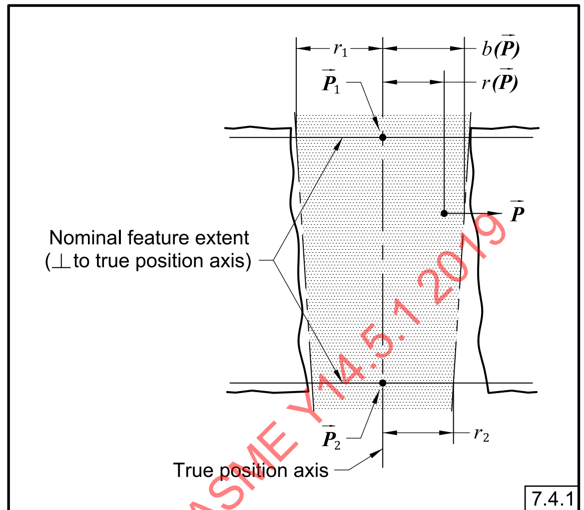


Table 7-5 Definition of Conical Tolerance Zone — Surface Interpretation

		Material Condition Basis	
		MMC or RFS	LMC
Feature Type	Internal	$r(\vec{P}) < b(\vec{P})$	$r(\vec{P}) > b(\vec{P})$
	External	$r(\vec{P}) > b(\vec{P})$	$r(\vec{P}) < b(\vec{P})$

Table 7-6 Size of Conical Tolerance Zone — Surface Interpretation

		Material Condition Basis		
	r_i	MMC	RFS	LMC
Feature Type	Internal	$r_{MMC} - \frac{t_i}{2}$	$r_{AM} - \frac{t_i}{2}$	$r_{LMC} + \frac{t_i}{2}$
	External	$r_{MMC} + \frac{t_i}{2}$	$r_{AM} + \frac{t_i}{2}$	$r_{LMC} - \frac{t_i}{2}$

Figure 7-8 Resolved Geometry (Axis) Interpretation of Conical Tolerance Zone for Holes at MMC or RFS

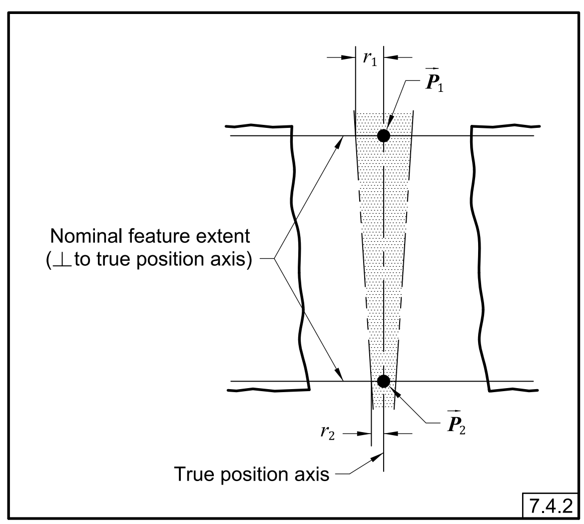


Table 7-7 Size of Conical Tolerance Zone — Resolved Geometry (Axis) Interpretation

		Material Condition Basis		
	r_i	MMC	RFS	LMC
Feature Type	**Internal**	$\frac{t_i}{2} + (r_{AM} - r_{MMC})$	$\frac{t_i}{2}$	$\frac{t_i}{2} + (r_{LMC} - r_{AMM})$
	External	$\frac{t_i}{2} + (r_{MMC} - r_{AM})$	$\frac{t_i}{2}$	$\frac{t_i}{2} + (r_{AMM} - r_{LMC})$

Table 7-8 Definition of Bidirectional Tolerance Zone — Surface Interpretation

		Material Condition Basis	
		MMC or RFS	LMC
Feature Type	**Internal**	$r(\vec{P}) < b$	$r(\vec{P}) > b$
	External	$r(\vec{P}) > b$	$r(\vec{P}) < b$

GENERAL NOTE: In this table, $r(\vec{P})$ is the distance from $\vec{P}$ to the resolved geometry of the tolerance zone boundary. The tolerance zone boundary is a cylinder for a hole at MMC or RFS and for shafts at LMC; it is a pair of parallel planes for shafts at MMC or RFS and for holes at LMC.

Table 7-9 Size of Bidirectional Tolerance Zone — Surface Interpretation

		Material Condition Basis		
	b	MMC	RFS	LMC
Feature Type	**Internal**	$r_{MMC} - \frac{t_0}{2}$	$r_{AM} - \frac{t_0}{2}$	$r_{LMC} + \frac{t_0}{2}$
	External	$r_{MMC} + \frac{t_0}{2}$	$r_{AM} + \frac{t_0}{2}$	$r_{LMC} - \frac{t_0}{2}$

Figure 7-9 Bidirectional Hole Tolerance at MMC With Cylindrical Tolerance Zones — Surface Interpretation

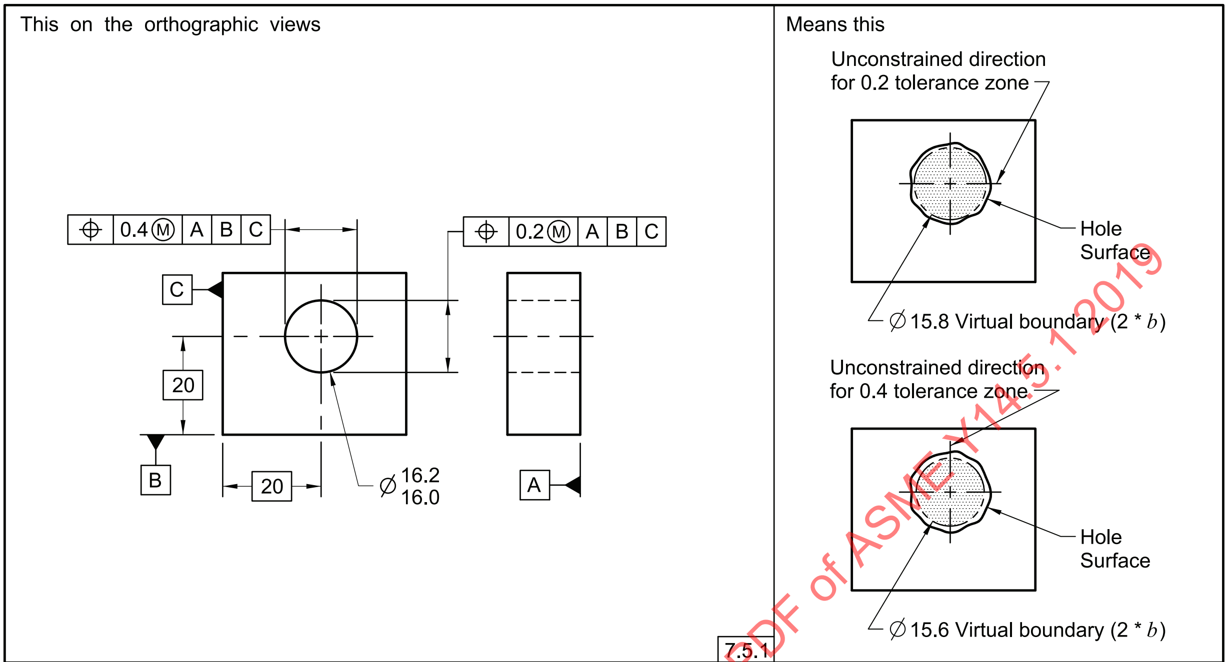


Figure 7-10 Bidirectional Shaft Tolerance at MMC With Parallel Plane Tolerance Zones — Surface Interpretation

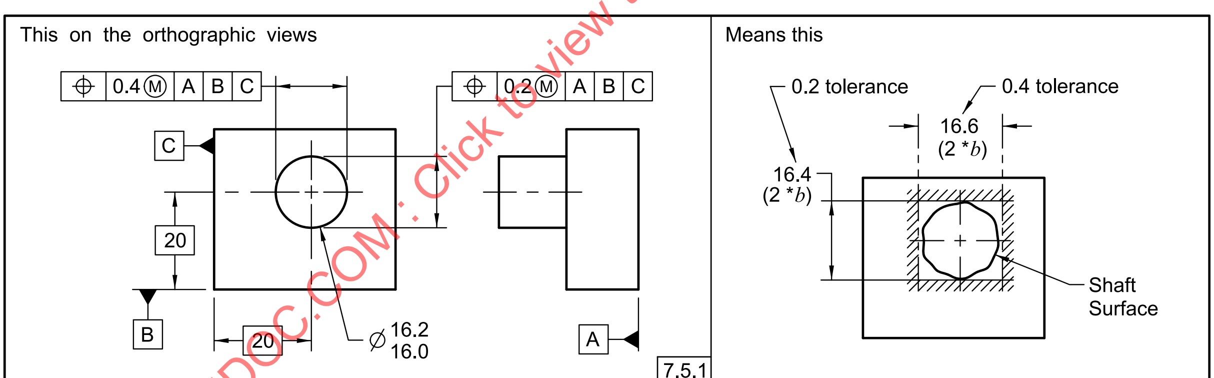


Table 7-10 Size of Bidirectional Tolerance Zone — Resolved Geometry (Axis) Interpretation

		Material Condition Basis		
	b	**MMC**	**RFS**	**LMC**
Feature Type	**Internal**	$\frac{t_0}{2} + (r_{AM} - r_{MMC})$	$\frac{t_0}{2}$	$\frac{t_0}{2} + (r_{LMC} - r_{AMM})$
	External	$\frac{t_0}{2} + (r_{MMC} - r_{AM})$	$\frac{t_0}{2}$	$\frac{t_0}{2} + (r_{AMM} - r_{LMC})$

Figure 7-11 Definition of the Tolerance Zone for Polar Bidirectional Tolerancing

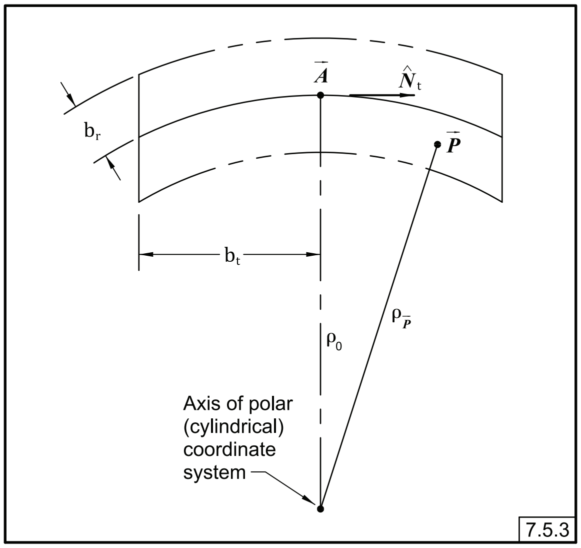


Table 7-11 Size of Polar Bidirectional Tolerance Zone — Resolved Geometry (Axis) Interpretation

		Material Condition Basis		
	b_r or b_t	MMC	RFS	LMC
Feature Type	Internal	$\frac{t}{2} + (r_{AM} - r_{MMC})$	$\frac{t}{2}$	$\frac{t}{2} + (r_{LMC} - r_{AMM})$
	External	$\frac{t}{2} + (r_{MMC} - r_{AM})$	$\frac{t}{2}$	$\frac{t}{2} + (r_{AMM} - r_{LMC})$

Figure 7-12 Tolerance Zone and Conformance, Elongated Hole at MMC — Tolerance Zone is the Right Cylinder Shown in Cross Section

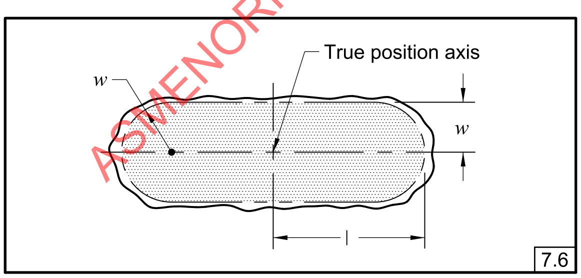
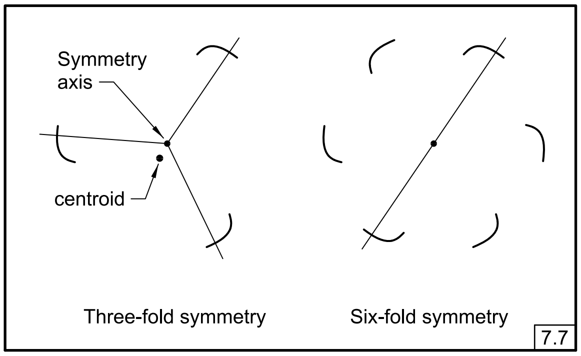


Table 7-12 Symmetry Elements for Obtaining Corresponding Feature Elements

Symmetry Type	Tolerance Type	Patterns of Symmetry Rays
Point	Concentricity	Rays from the datum point
Axis	Concentricity	Rays from, and perpendicular to, the datum axis
Plane	Symmetry	Rays from, and perpendicular to, the datum plane

Figure 7-13 Rays Are Arranged in the Lowest Order of Symmetry About an Axis or a Point



Section 8
Tolerances of Profile

8.1 GENERAL

This Section establishes the principles and methods for mathematical evaluation of ASME Y14.5-2009 dimensioning and tolerancing applicable to the control of profile.

8.2 PROFILE

Profile tolerances define tolerance zones to control surfaces relative to a true profile. Unless otherwise specified, profile tolerance zones maintain a basic relationship to the true profile and any datums referenced. This enables profile tolerance zones to always control form and, where applicable, size (curvature), orientation, and location of the considered feature.

8.2.1 Types of Profile Tolerances

A profile tolerance may be applied to the entire surface of a part, multiple features, individual surfaces, or to individual profiles taken at various cross sections through a part. The two types of profile tolerances are profile of a surface and profile of a line, and they are explained in paras. 8.2.1.1 and 8.2.1.2.

8.2.1.1 Profile of a Surface. Per ASME Y14.5-2009
The tolerance zone established by the profile of a surface tolerance is three-dimensional (a volume), extending along the length and width (or circumference) of the considered feature or features. [8.2.1.1]

For profile of a surface, the true profile is comprised of surface geometry. The controlled component is the entire surface of the actual feature(s).

8.2.1.2 Profile of a Line. No mathematization of the definition, conformance, or actual value of profile of a line is provided in this Standard.

8.3 TOLERANCE ZONE BOUNDARIES

Uniform, bilateral, unequally disposed, or nonuniform tolerance zones may be defined by profile tolerances.

8.3.1 Uniform Tolerance Zones

Per ASME Y14.5-2009
A uniform tolerance zone is the distance between two boundaries equally or unequally disposed about the true profile or entirely disposed on one side of the true profile. Profile tolerances apply normal (perpendicular) to the true profile at all points along the profile. The boundaries of the tolerance zone follow the geometric shape of the true profile. [8.3.1]

(a) Definition. A profile tolerance zone for a continuous true profile is constructed by sweeping a line segment of length t_0, where t_0 is the specified tolerance, along each point on the true profile. The line segment is kept normal to the true profile at each point. If the line segment intersects the true profile at another point, the line segment shall be truncated at that intersection. The profile tolerance zone is the union of line segments obtained from all points on the basic surface. A maximum material boundary (MMB) and a least material boundary (LMB) are created, each one a locus of endpoints of the line segments.

The disposition of the generating line segment follows the disposition indicated by the tolerance specification. See Table 8-1 and Figures 8-1 through 8-4.

(1) For equally disposed tolerances, the line segment is centered on the basic surface with equal extension in both directions.

(2) For unilateral and unequally-disposed tolerances, the line segment is disposed in the manner indicated by the unequally-disposed symbol Ⓤ or graphical indication. Several different dispositions are defined for a profile tolerance t_0 with a value t_u following the unequally-disposed symbol.

(b) Conformance. A feature conforms to a profile tolerance t_0 if all points on the actual surface are within the tolerance zone described above.

(c) Actual Value. The actual value of a profile tolerance is based on an enveloping zone called the *actual zone* that is generated in the same way as the tolerance zone. This concept applies in the same way to equally disposed, unequally disposed, and unilateral profile specifications. The generating line segment of the tolerance value t_0 is lengthened or shortened by an equal amount at each end. The length change at each end is called the growth parameter g. The line segment for the actual zone has a length equal to $t_0 + 2g$. The actual zone has the minimum g necessary to contain the actual surface.

(1) If the actual zone is contained within the tolerance zone, the growth parameter g is negative.

(2) If the actual zone is not contained within the tolerance zone, g is positive.

(3) If the actual zone is equivalent to the tolerance zone, g = 0.

NOTE: Any necessary truncation is performed after the lengthening or shortening of the line segments.

The actual value of a profile tolerance for a single feature is the value of $t_0 + 2g$ for the enveloping zone to which the actual surface will conform. See Figures 8-5 through 8-8.

NOTE: This Section defines the actual value of a uniform profile tolerance in the context of a single feature in a given candidate datum reference frame. Applications involving multiple features and optimization within degrees of freedom are addressed in para. 8.4.1.5 of this Standard.

The value after the Ⓤ symbol for the actual zone is not part of the actual value definition, but can be calculated using the expression ($t_u + g$).

8.4 PROFILE APPLICATIONS

Subsection 8.3 explained the profile tolerance zone and actual value in the context of a single feature in a fully constrained datum reference frame. Profile tolerances can also be applied to multiple features, with a variety of possible datum feature constraints and tolerance zone transformations. These are most easily explained using the system concept, in which the profile tolerance is treated as a system with degrees of freedom and constraints. This approach allows optimization and actual value calculation for applications with mixed tolerance values and combined controls.

8.4.1 Optimization of Profile Tolerance Systems

Conformance and actual value calculation for a profile tolerance system is based on the concept of optimization within constraints. The actual surface geometry and the tolerance zones for the profile tolerances in the system are fitted to each other within the applicable constraints. Profile tolerance systems include the following:

(a) basic reference-body with true profile(s)

(b) tolerance zone(s) for considered feature(s)

(c) actual part geometry with actual considered feature surface(s)

(d) actual datum feature surfaces (if applicable)

(e) datum feature simulators or datum target simulators (if applicable)

(f) datums and a datum reference frame (if applicable)

8.4.1.1 Basic Reference-Body. This is the design geometry (para. 1.1.1).

8.4.1.2 Candidate Spatial Relationships. ASME Y14.5-2009 uses the term "datum feature shift" to describe relative movement between the datum feature(s) and a datum reference frame. In this Section, the term "candidate spatial relationship" is used to describe a particular instance of rotation and translation between the actual part geometry and the basic reference-body. This generalizes the concept of datum feature shift, to apply to profile applications in which a datum reference frame is not present (i.e., no datum features are referenced). See Figures 8-11, 8-12, 8-15, and 8-16.

8.4.1.3 Candidate Tolerance Zone Transformations. By default, profile tolerance zones remain static relative to the true profile. With composite profile tolerancing, the feature-relating tolerance zones are constrained in rotation only and are thus permitted to translate.

This is an example of a tolerance zone transformation, in which the tolerance zone framework is permitted to translate relative to the datums (and datum reference frame). In this Standard, the term candidate tolerance zone transformation is used to describe a particular transformation of the tolerance zone relative to the basic reference-body. See para. 8.4.7 of this Standard for details on composite profile.

8.4.1.4 Candidate Configurations. In this Standard, the generic term candidate configuration is used to describe a particular state of a profile tolerance system. This can include a candidate spatial relationship, candidate tolerance zone transformations, or both.

8.4.1.5 Default Optimization Criteria for Calculation of Actual Values. For most geometric characteristics applied to single feature (profile or otherwise), the actual value is the smallest tolerance to which the feature will conform. In terms of optimization, the objective function is to minimize the size of the zone that will just envelop the feature. For profile tolerance systems involving multiple features and mixed tolerance values, this concept cannot be uniquely applied and must be generalized. In each candidate configuration of such systems, candidate actual values for each characteristic can be calculated.

In this Standard, the default optimization method is to minimize the maximum value of the growth parameter g for the geometric characteristics in the system. This represents a generalization of the single-feature concept of minimizing the size of the enveloping zone. Actual values are defined as the candidate actual values in the candidate configuration in which the largest value of g for any feature in the system is minimized.

8.4.2 Constraint Properties of Profile Tolerance Zones

A profile tolerance zone is defined in relation to a theoretically exact true profile that is considered rigid. The tolerance zone has perfect form and by default is not permitted to transform (translate, rotate, or progress) relative to the true profile. This enables the profile zone to control form and, where applicable, size of the considered feature. See Figures 8-9 through 8.12.

8.4.3 Effect of Pattern Creation (Grouping) Mechanisms

Pattern creation mechanisms (ALL AROUND, ALL OVER, between points, *nX*, *n* SURFACES, INDICATED) have the following system-level effects:

(a) All profile characteristics in the pattern are treated as one profile tolerance system

(b) All profile tolerance zones in the pattern must be evaluated simultaneously, in a common candidate configuration.

The basic reference-body provides a rigid framework for mutual constraint of the profile tolerance zones. Each feature's true profile is a subset of the basic reference-body, and all of the true profiles in the profile tolerance system are therefore basically related. The tolerance zones are not permitted to transform relative to the true profile. See Figures 8-13 through 8-16. The combination of basically related tolerance zones and simultaneous evaluation enables the control of mutual orientation and mutual location of the considered features, even in the absence of a datum reference frame.

8.4.4 Effect of Individual Profile Specifications

Multiple profile tolerances for which a grouping mechanism does not apply have the following properties:

(a) Each profile tolerance is each treated as a distinct requirement. See Figures 8-17 and 8-18.

(b) Each profile tolerance may be optimized individually, i.e., actual values may be calculated in different candidate configurations. See Figures 8-19 and 8-20.

8.4.5 Datum Feature References

Referencing a datum feature in a profile feature control frame adds the following to the profile tolerance system:

(a) basic datum feature surfaces (subsets of the basic reference-body).

(b) datum feature simulators. Unless otherwise specified, a datum feature simulator is a surface coincident with or derived from the basic datum feature with the surface normal pointing in the opposite direction.

(c) datums and a datum reference frame.

(d) actual datum feature surfaces.

(e) requirements for contact between the actual datum features and the simulators, as defined in ASME Y14.5-2009 and further explained in Section 4 of this Standard. These may involve maximum contact (RMB references) or envelopment (MMB or LMB references).

The requirements for contact impose a constraint on the system that reduces the set of valid candidate spatial relationships. See Figure 8-21 through 8-24.

8.4.6 Effect of Simultaneous Requirements

Where simultaneous requirements apply, all profile tolerances in the system must be optimized simultaneously in a common candidate spatial relationship, as described in para. 8.4.1.5. See Figures 8-25 through 8-28.

8.4.7 Composite Profile

Per ASME Y14.5-2009

This provides a composite application of profile tolerancing for the location and constraint (rotation and translation) of a feature pattern (PLTZF) as well as the interrelation (location, size, form, orientation) or profiled features within these patterns (FRTZF). [8.6.1.3]

The toleranced feature shall lie within both the PLTZF and the FRTZF.

Each complete horizontal segment of a composite profile feature control frame constitutes a separately verifiable component of multiple interrelated requirements.

In terms of the system concept, the profile tolerance in each segment of a composite feature control frame may be evaluated as a separate profile tolerance system.

8.4.7.1 Pattern Locating Tolerance Zone Framework (PLTZF). Conformance and actual value are the same as a single segment feature control frame.

8.4.7.2 Feature Relating Tolerance Zone Framework (FRTZF). The feature relating tolerance zone framework has a slightly different behavior, in that only its rotation is controlled by the datums. Per ASME Y14.5-2009

If datums are specified in the lower segment(s), they govern the rotation of the FRTZF relative to the datums and within the boundaries established and governed by the PLTZF. [8.6.1.3(b)(2)]

In terms of the profile tolerance system, the FRTZF has an additional transformation:

– The FRTZF may freely translate relative to the basic reference-body, in order to achieve conformance or optimal actual value. The tolerance zone shall not progress or rotate relative to the basic reference-body. These properties make the FRTZF capable of refining form, size, and orientation without refining location. See Figures 8-29 through 8-32.

8.5 EXTENSION OF TOLERANCE ZONE BOUNDARIES FOR SHARP CORNERS

Per ASME Y14.5-2009

Where a profile tolerance encompasses a sharp corner, the tolerance zone extends to the intersection of the boundary lines. [8.3.1]

In this Standard, a sharp corner is considered to be a point at which the true profile is not tangent continuous. In such cases, the boundaries are extended until they intersect. This defines an extension to the tolerance zone. For planar boundaries, a planar extension is created for each boundary and trimmed at the intersections. For curved boundaries, a default method of creating the extension geometry (linear, constant curvature, other) is not defined. Enveloping zones for actual value calculation should use the same extension method used for creating the tolerance zone. See Figures 8-33 and 8-34.

8.6 NONUNIFORM TOLERANCE ZONE

(a) Definition. Per ASME Y14.5-2009

A nonuniform tolerance zone is a maximum material boundary and a least material boundary, of unique shape, that encompasses the true profile. These boundaries are defined in a CAD file or by basic dimensions on a drawing with phantom lines to indicate the tolerance zone. The term "NONUNIFORM" replaces the tolerance value within the feature control frame." [8.3.2]

(b) Conformance. A feature conforms to a nonuniform profile tolerance if all points on the actual surface are within the specified tolerance zone.

(c) Actual Value. There is no unique tolerance value associated with a nonuniform tolerance zone, therefore a unique actual value is not defined.

Table 8-1 Table of Profile Tolerance Dispositions

Tolerance Value	Disposition	t_u
t_0	Equally disposed	$t_u = t_0/2$ (implied)
t_0	Unequally disposed	$0 < t_u < t_0$
t_0	Unilateral (outside)	$t_u = t_0$
t_0	Unilateral (inside)	$t_u = 0$

Figure 8-1 Tolerance Zone Derivation — Equally Disposed Profile

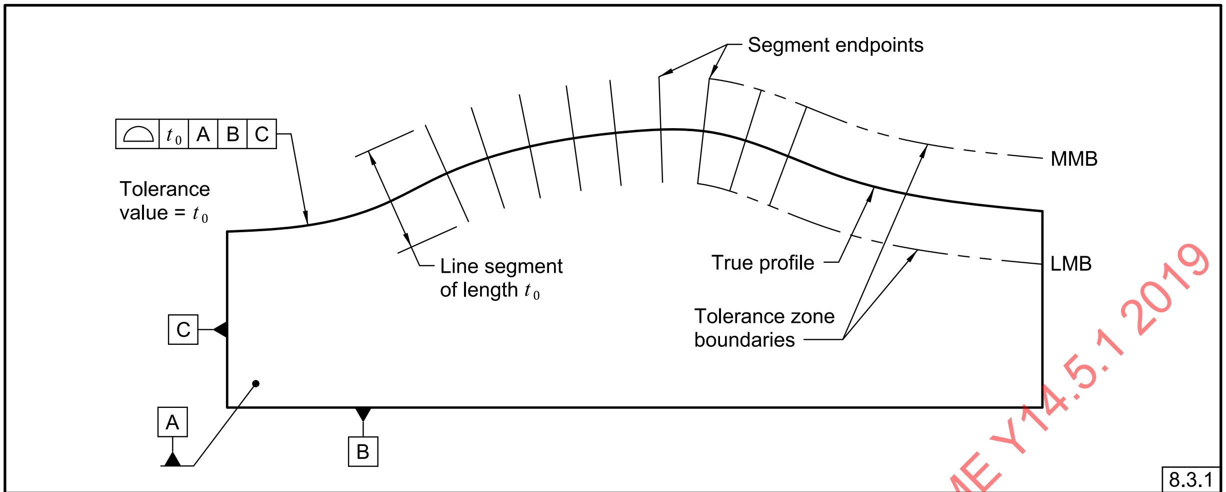


Figure 8-2 Tolerance Zone Derivation — Unequally Disposed Profile

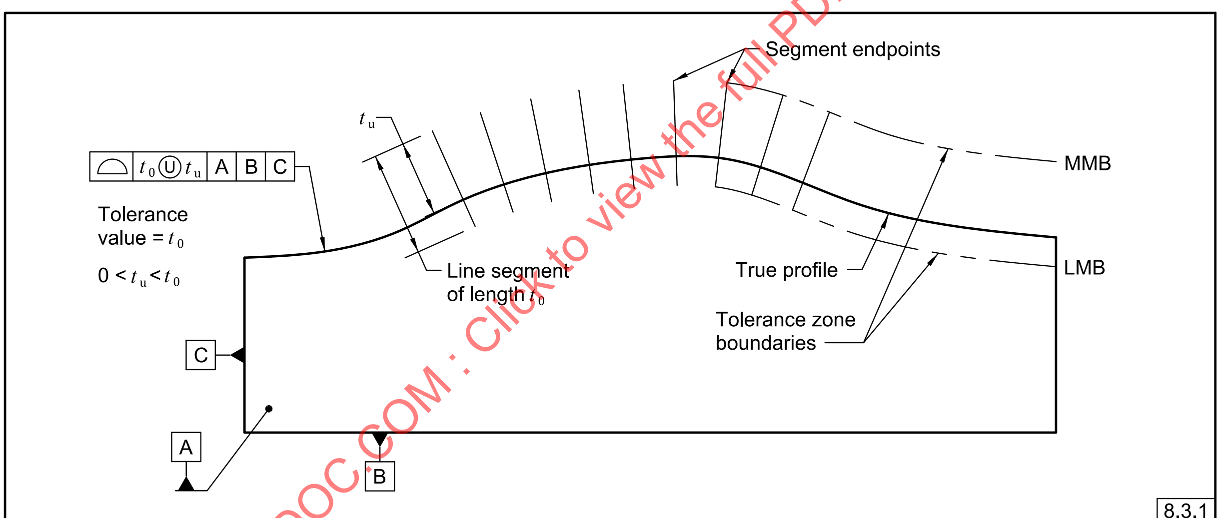


Figure 8-3 Tolerance Zone Derivation — Unilaterally Disposed Profile (Outside)

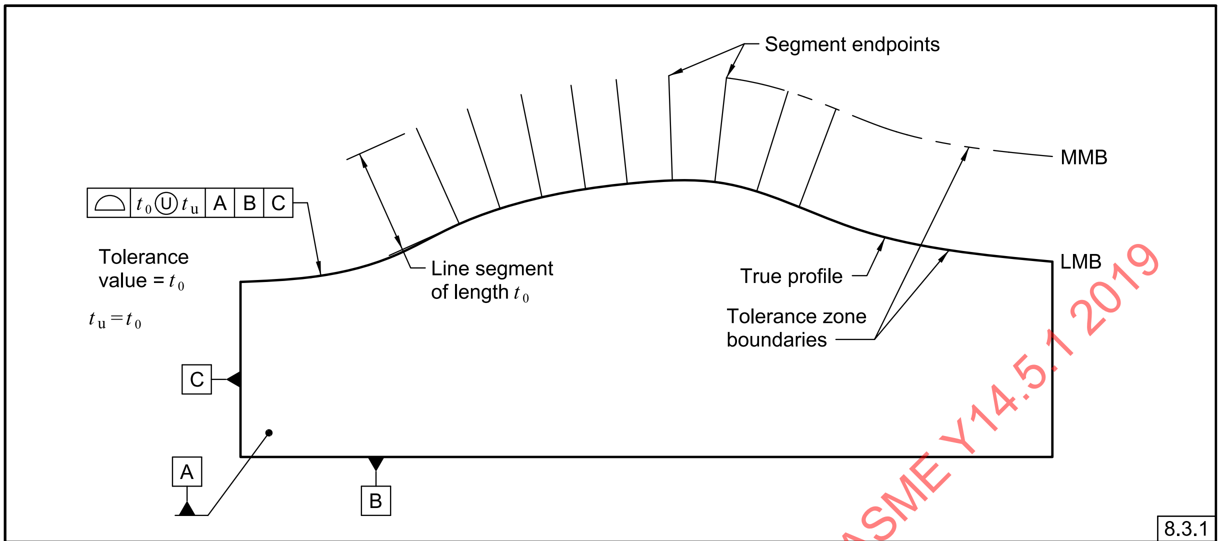


Figure 8-4 Tolerance Zone Derivation — Unilaterally Disposed Profile (Inside)

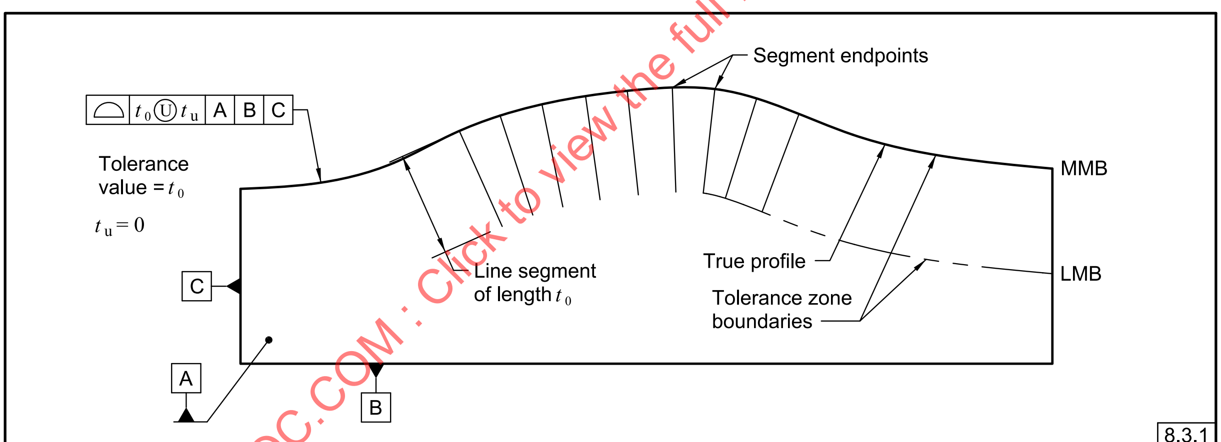


Figure 8-5 Actual Zone Definition for Equally Disposed Profile — Example of Conformance

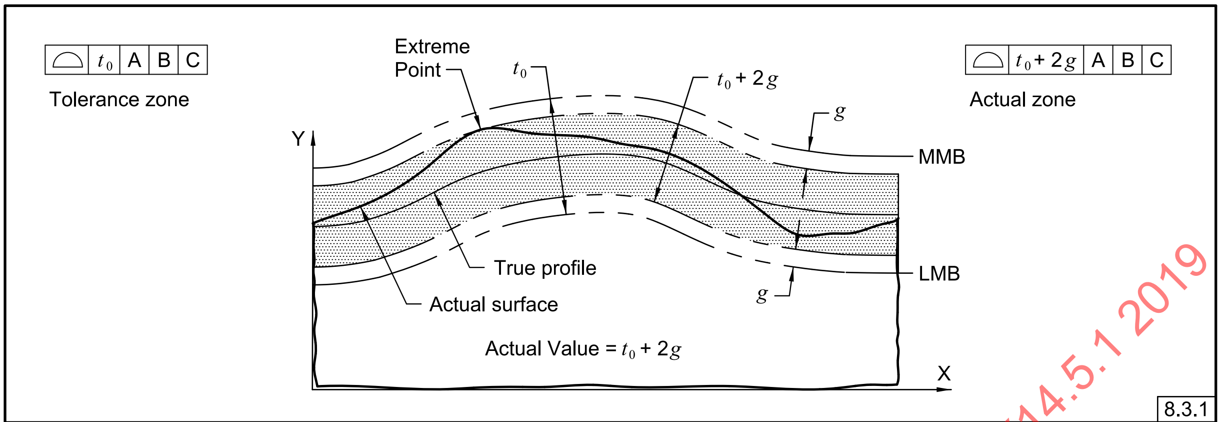


Figure 8-6 Actual Zone Definition for Unequally Disposed Profile — Example of Conformance

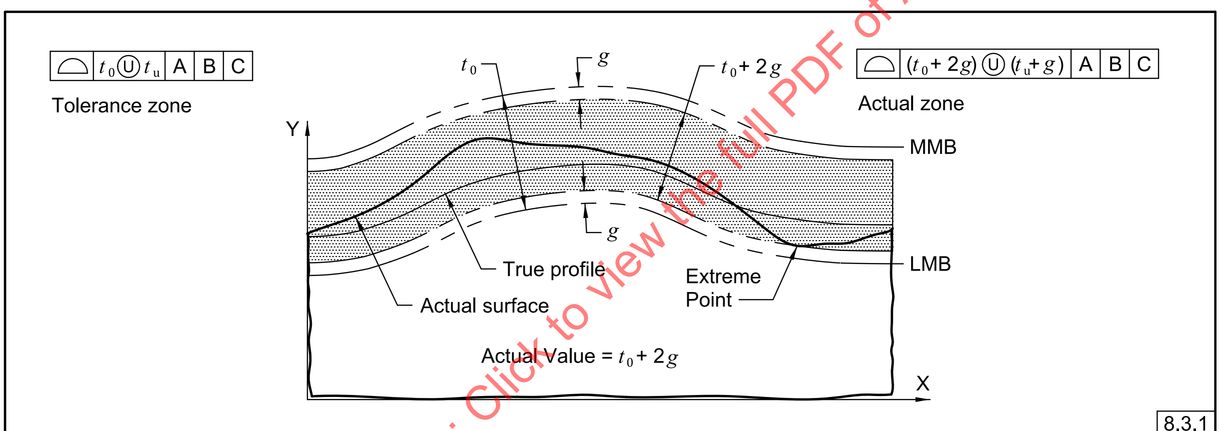


Figure 8-7 Actual Zone for Unilateral (Outside) Profile — Example of Nonconformance

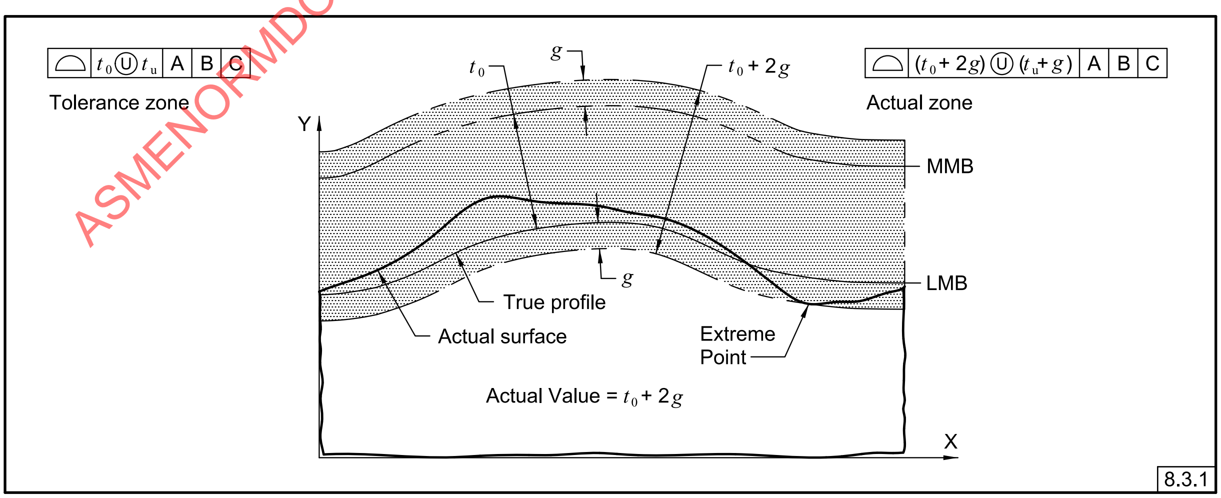


Figure 8-8 Actual Zone for Unilateral (Inside) Profile — Example of Nonconformance

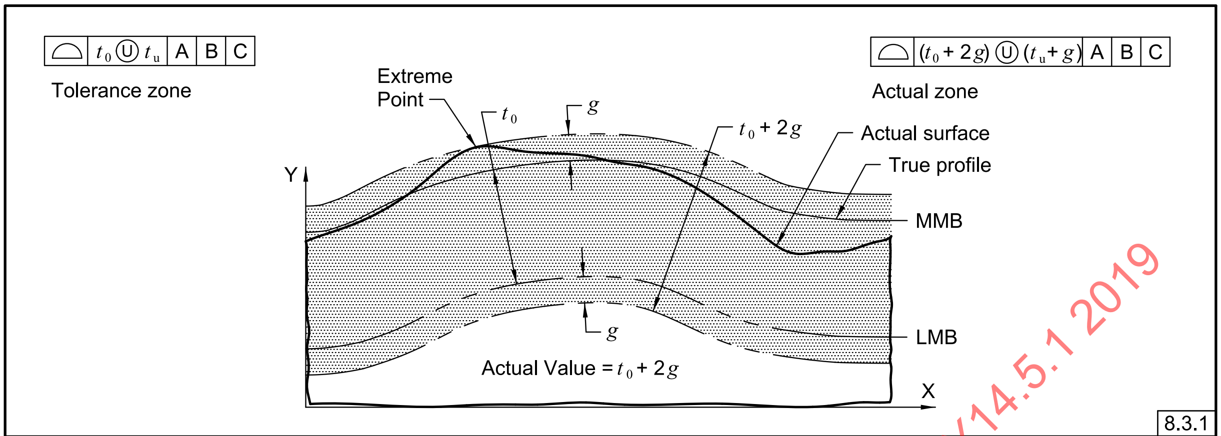


Figure 8-9 Profile Tolerance for a Single Feature Without a Datum Reference Frame

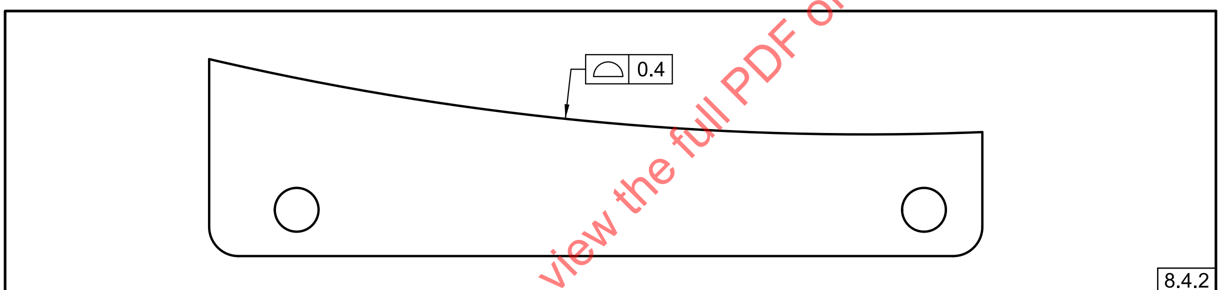


Figure 8-10 Profile Tolerance Zone for a Single Feature Without a Datum Reference Frame

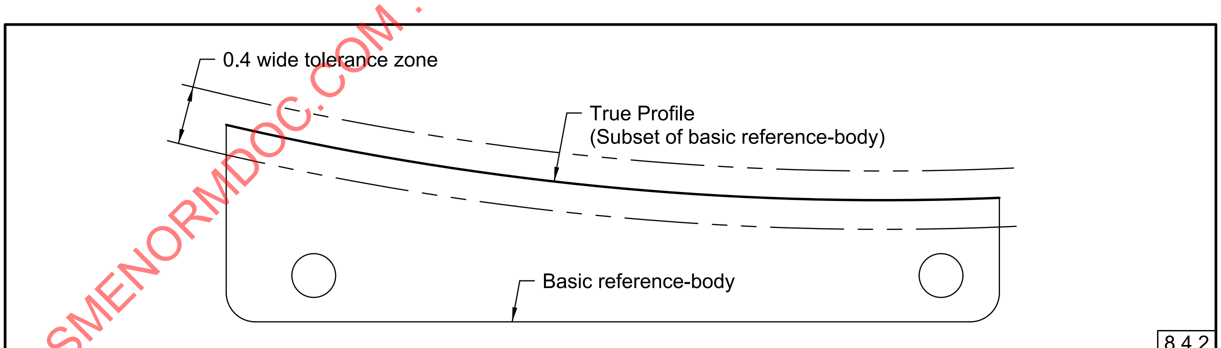


Figure 8-11 Candidate Configuration #1 (System Not Optimized)

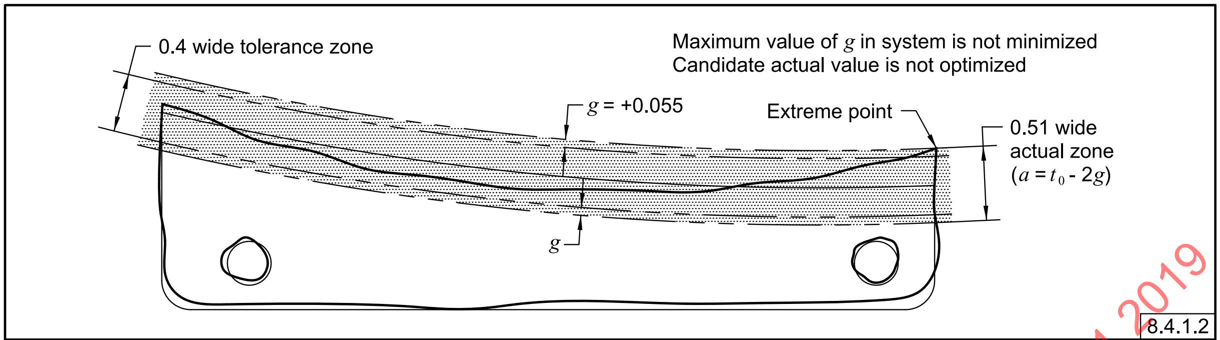


Figure 8-12 Candidate Configuration #2 (System Optimized)

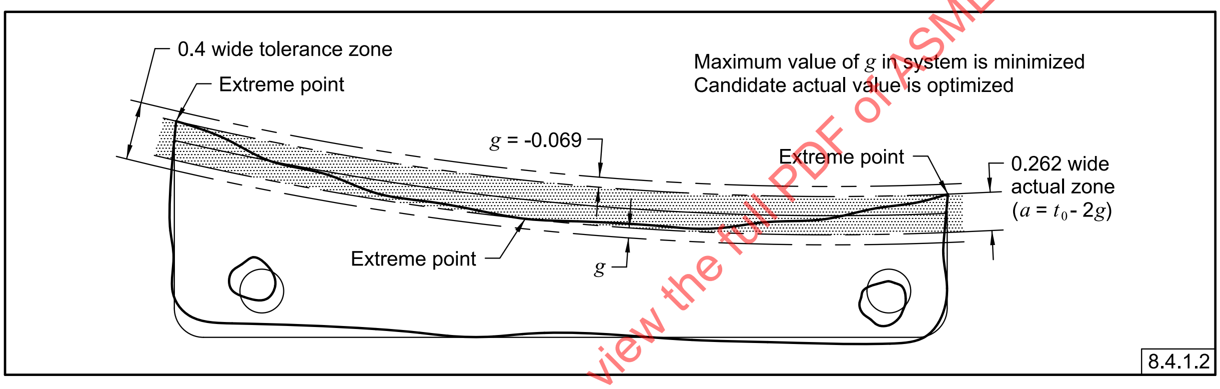


Figure 8-13 Actual Values in a Multi-Feature Profile Tolerance System — Specification

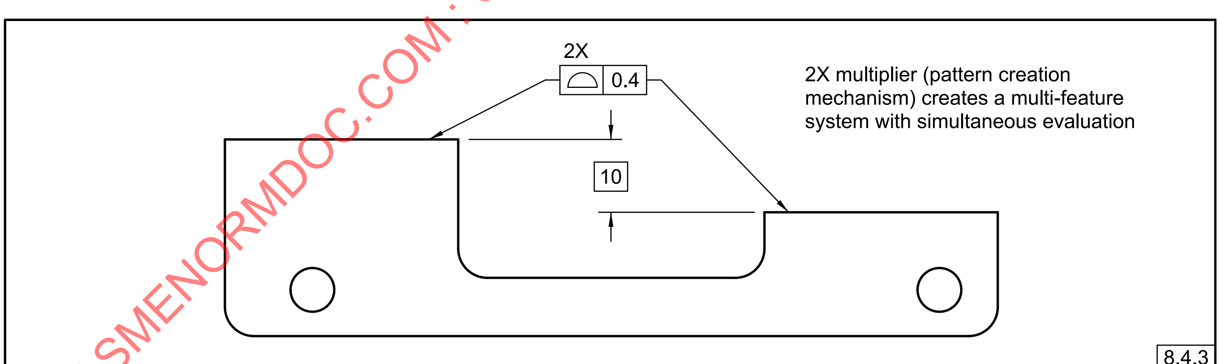


Figure 8-14 Actual Values in a Multi-Feature Profile Tolerance System — Basically Related Profile Tolerance Zones

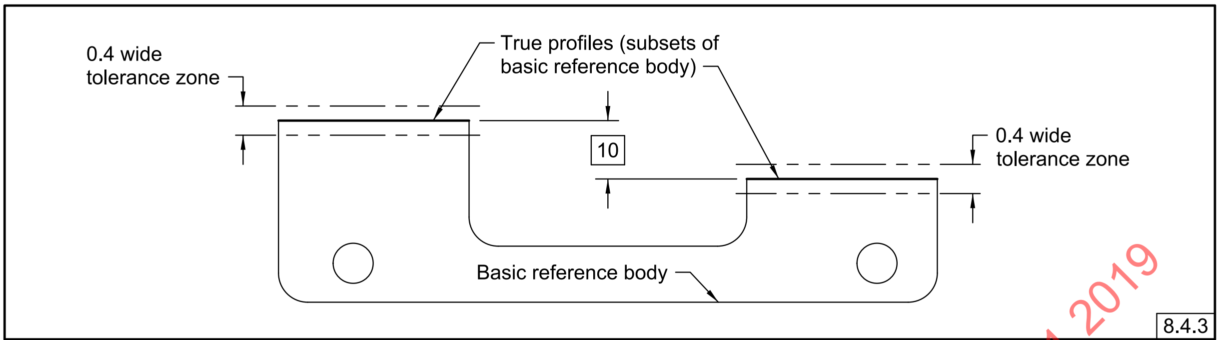


Figure 8-15 Actual Values in a Multi-Feature Profile Tolerance System — Candidate Configuration #1 (System Not Optimized)

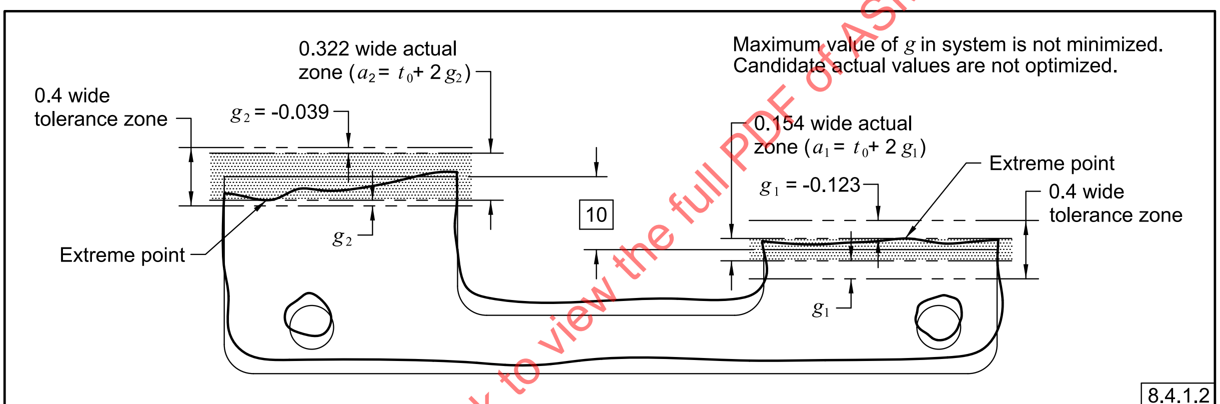


Figure 8-16 Actual Values in a Multi-Feature Profile Tolerance System — Candidate Configuration #2 (System Optimized)

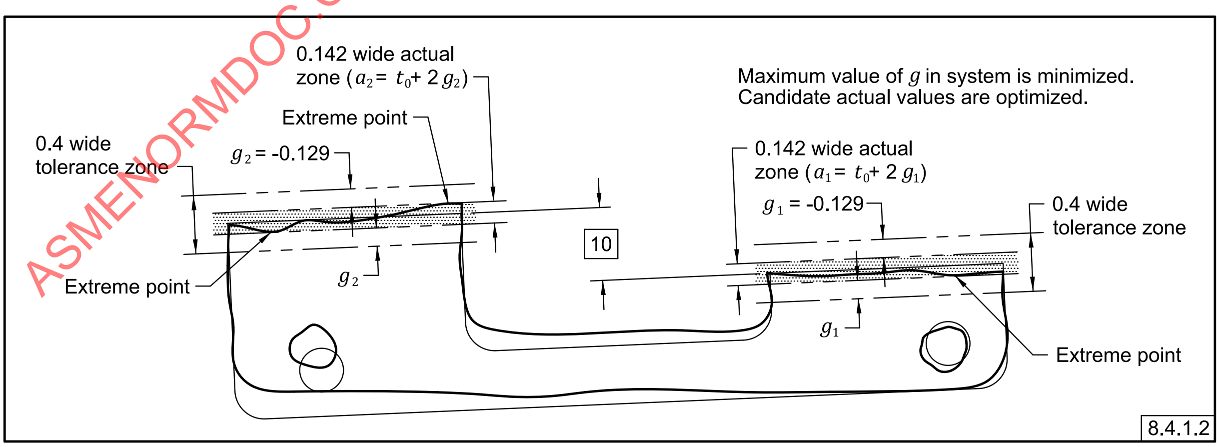


Figure 8-17 Individual Requirements for Profile — Specification

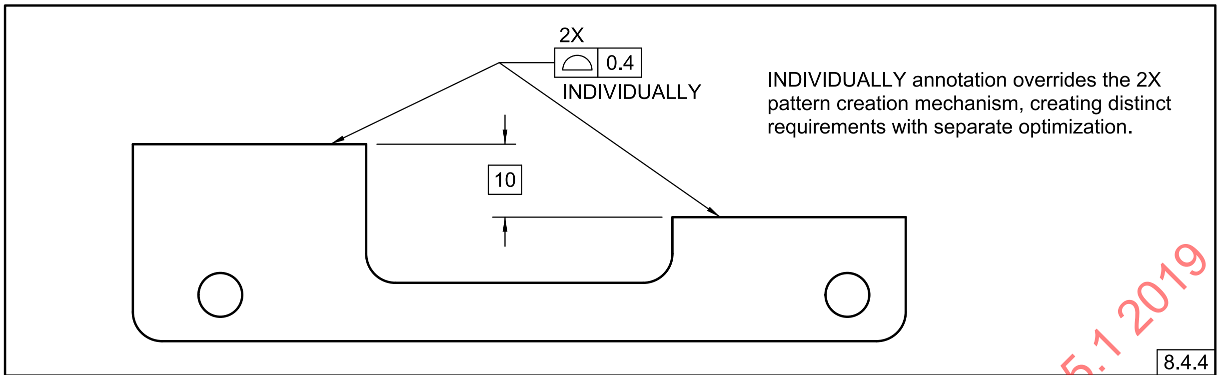


Figure 8-18 Individual Requirements for Profile — Tolerance Zones

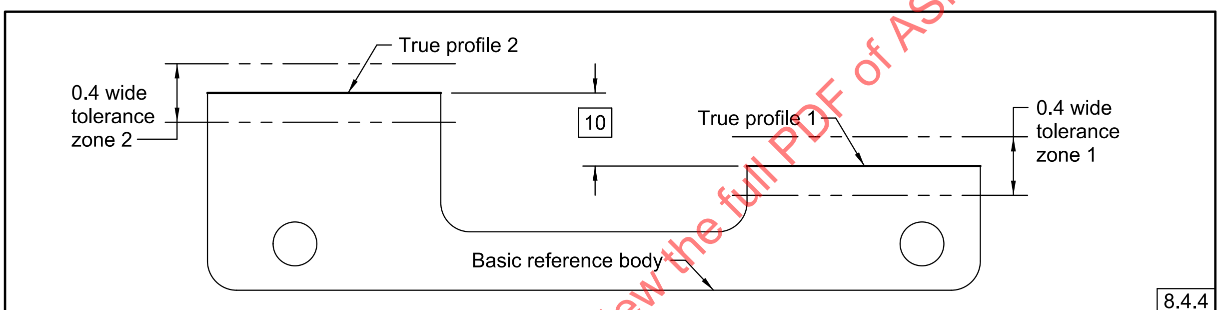


Figure 8-19 Individual Requirements for Profile — Individual Requirement 1

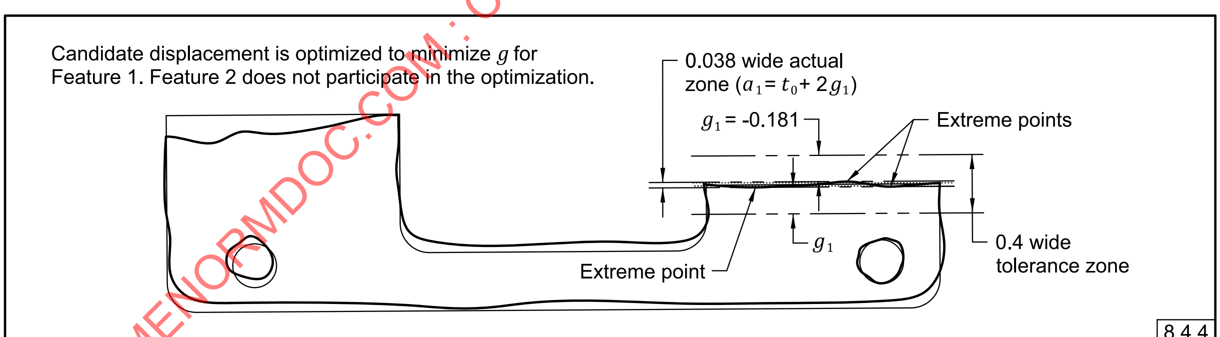


Figure 8-20 Individual Requirements for Profile — Individual Requirement 2

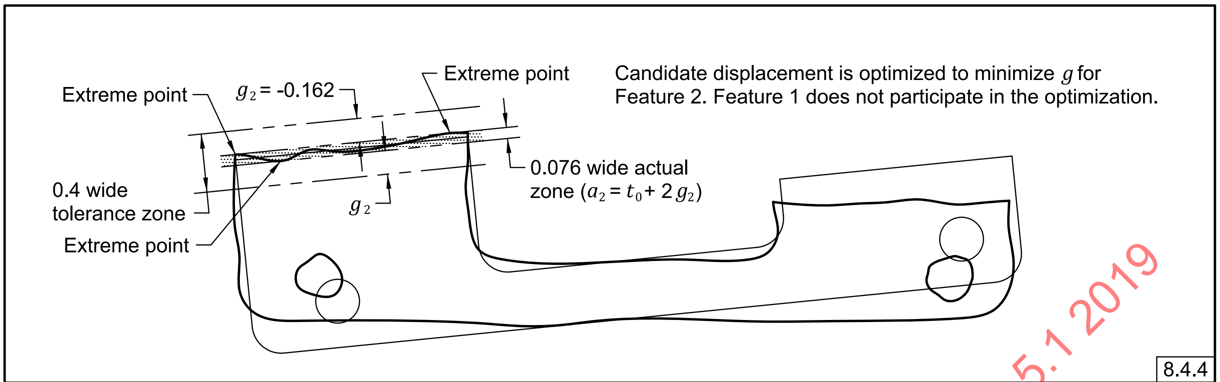


Figure 8-21 Datum Feature References With Profile — Specification

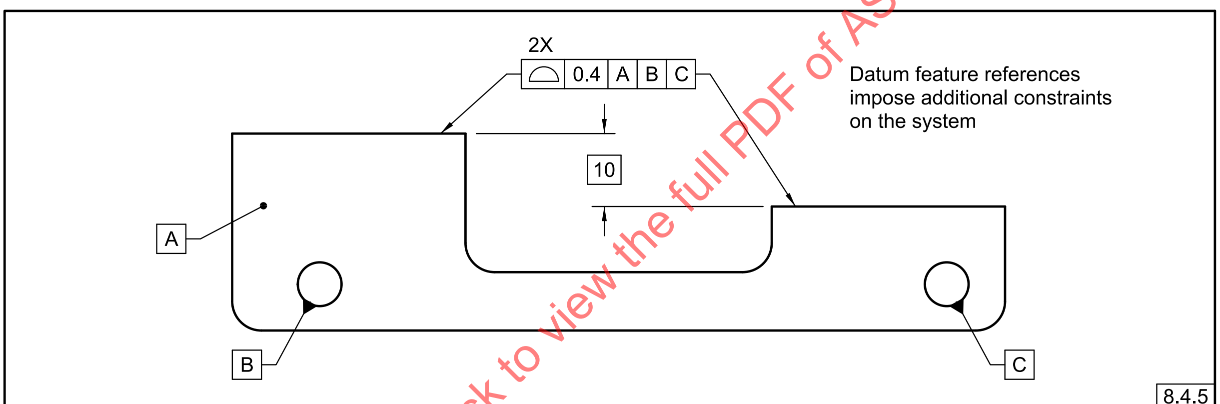


Figure 8-22 Datum Feature References With Profile — Tolerance Zones and Simulators

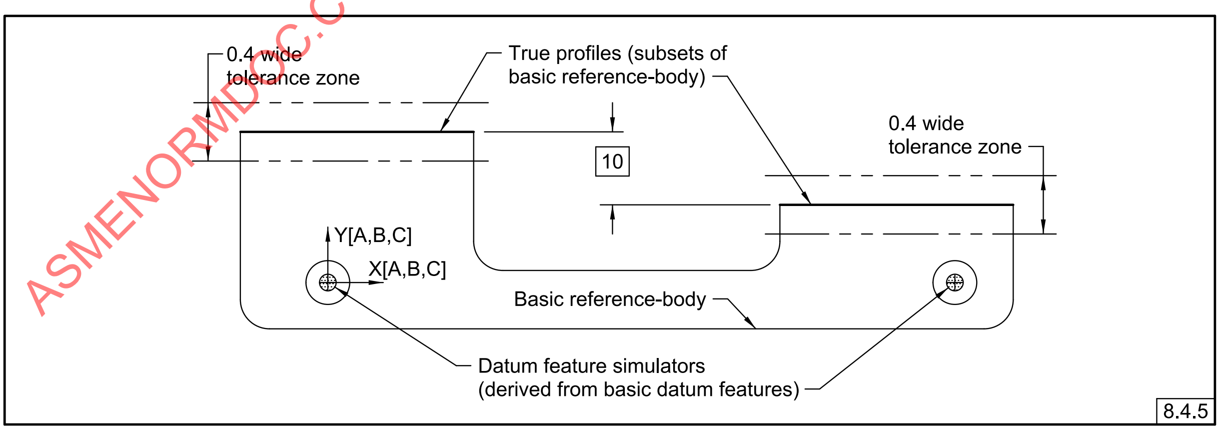


Figure 8-23 Datum Feature References With Profile — Invalid Candidate Configuration

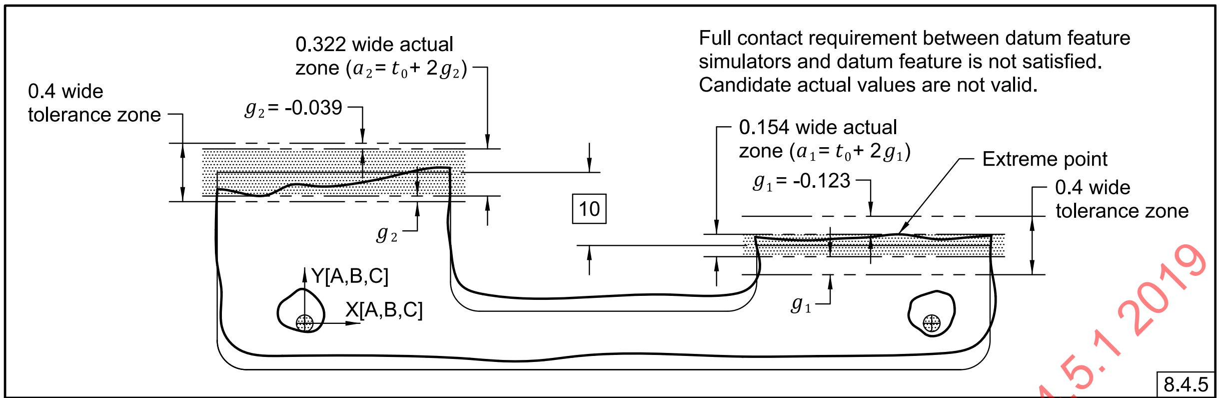


Figure 8-24 Datum Feature References With Profile — Valid Candidate Configuration

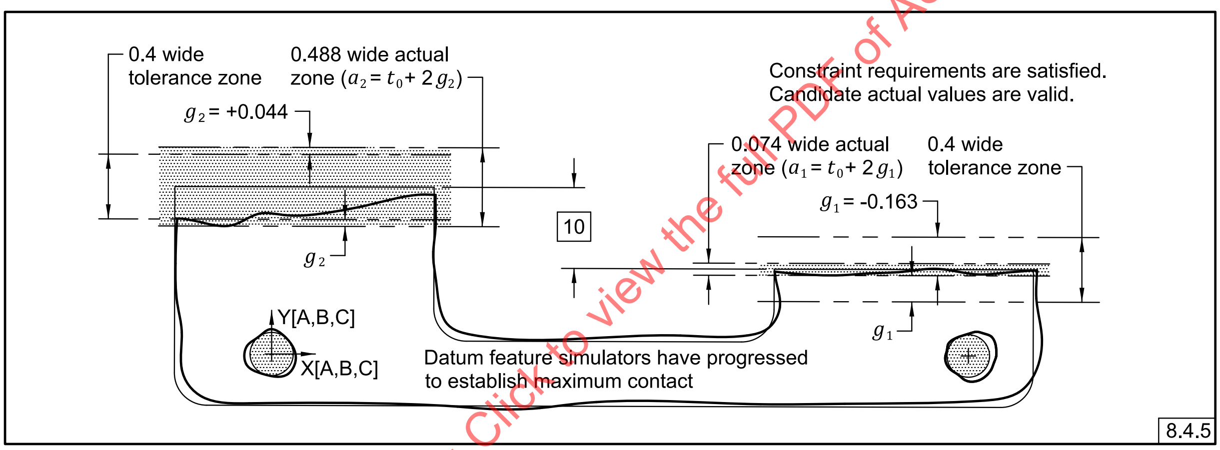


Figure 8-25 Simultaneous Requirements for Profile — Specification

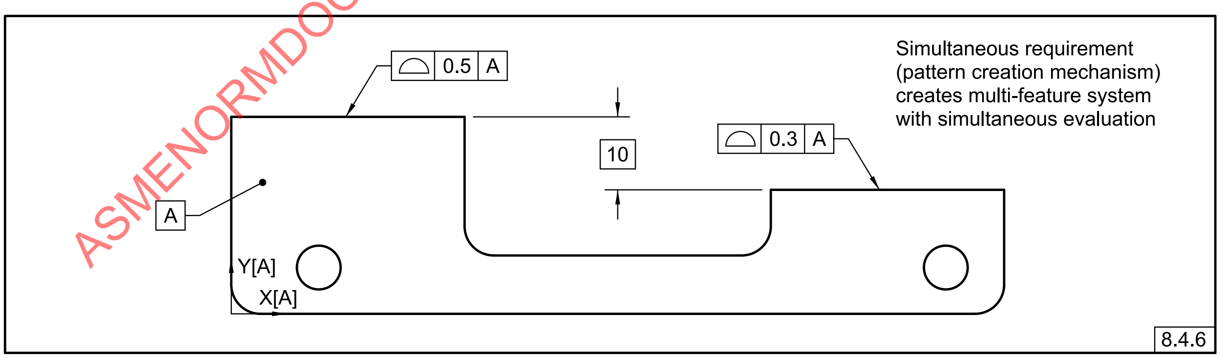


Figure 8-26 Simultaneous Requirements for Profile — Tolerance Zones

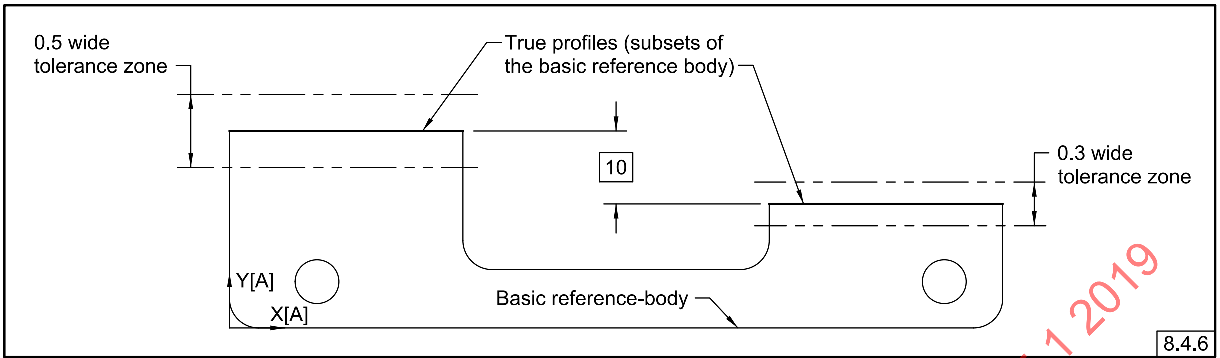


Figure 8-27 Simultaneous Requirements for Profile (System Not Optimized)

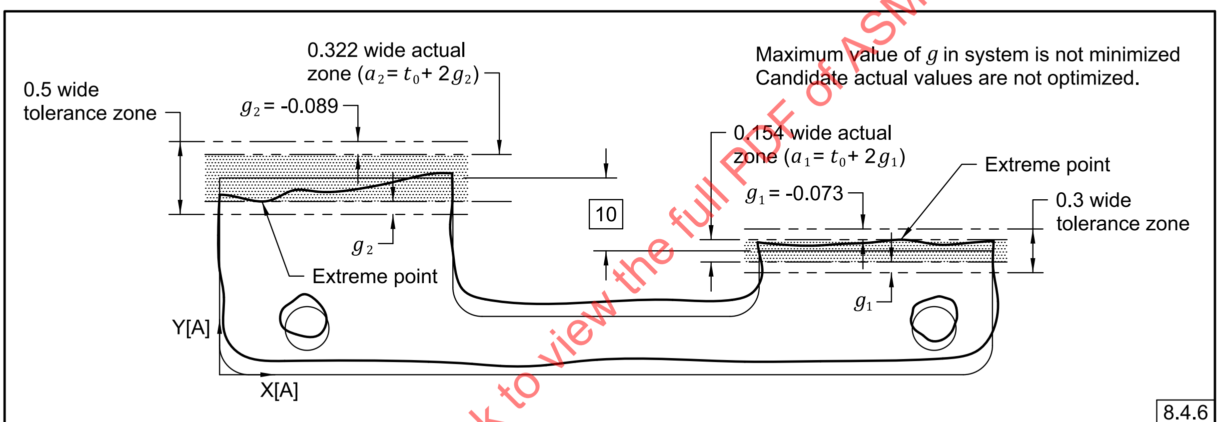


Figure 8-28 Simultaneous Requirements for Profile (System Optimized)

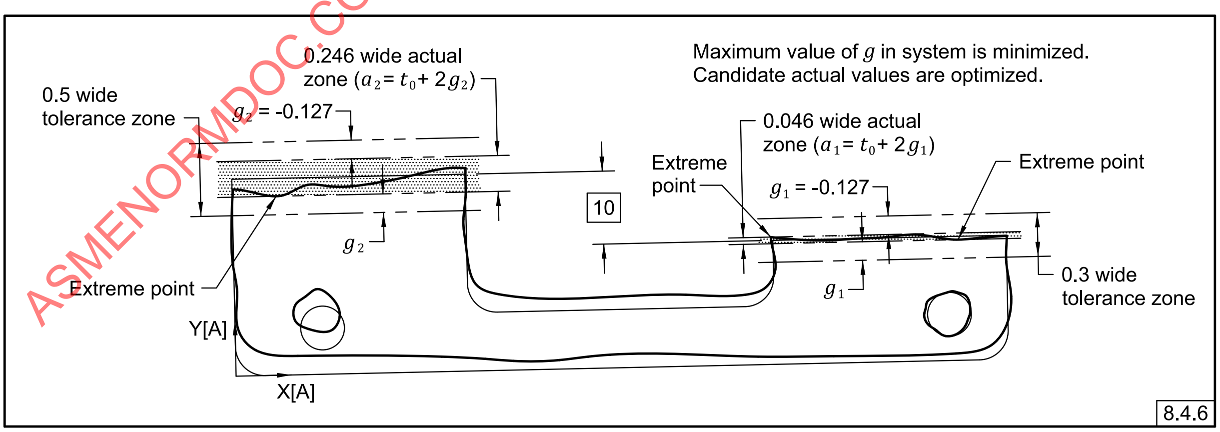


Figure 8-29 Composite Profile Lower Segment — Specification

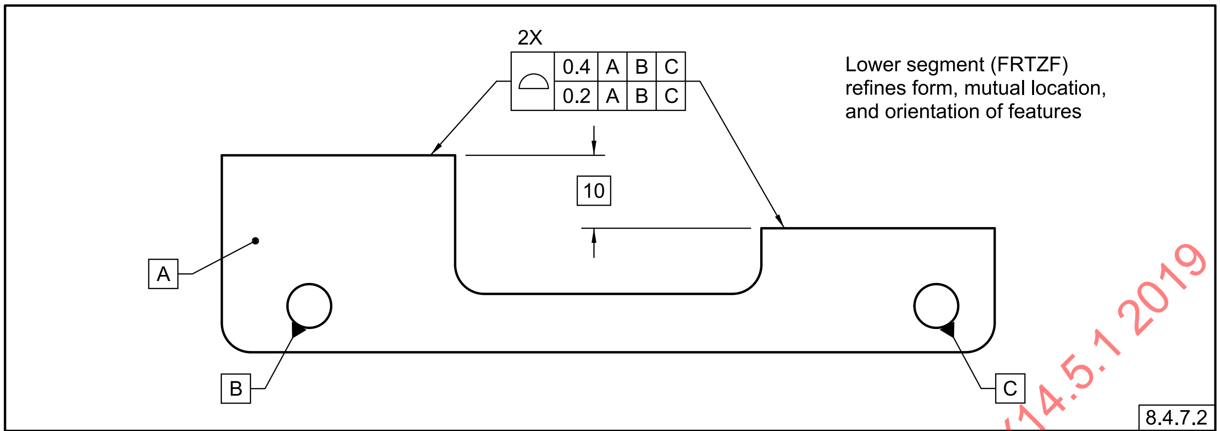


Figure 8-30 Composite Profile Lower Segment —Tolerance Zones (FRTZF)

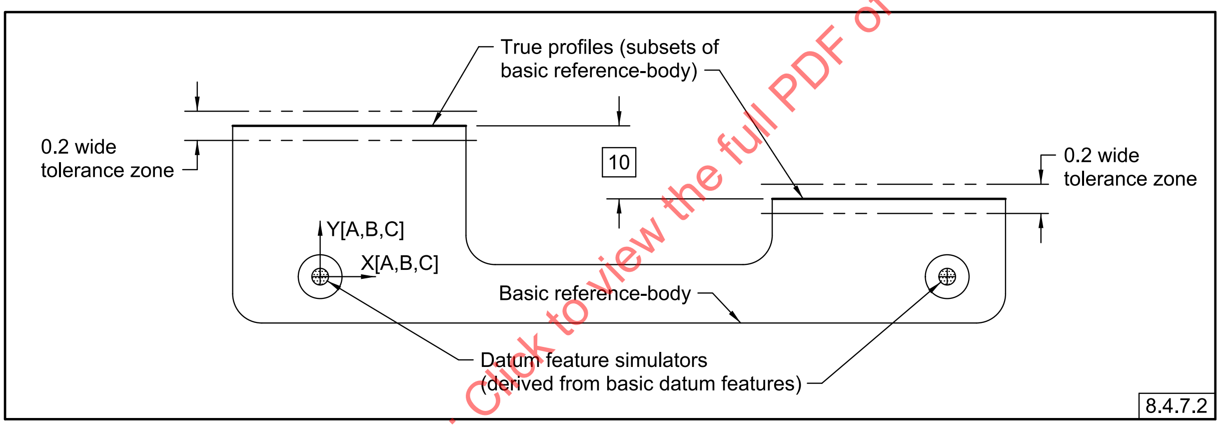


Figure 8-31 Composite Profile Lower Segment (System Not Optimized)

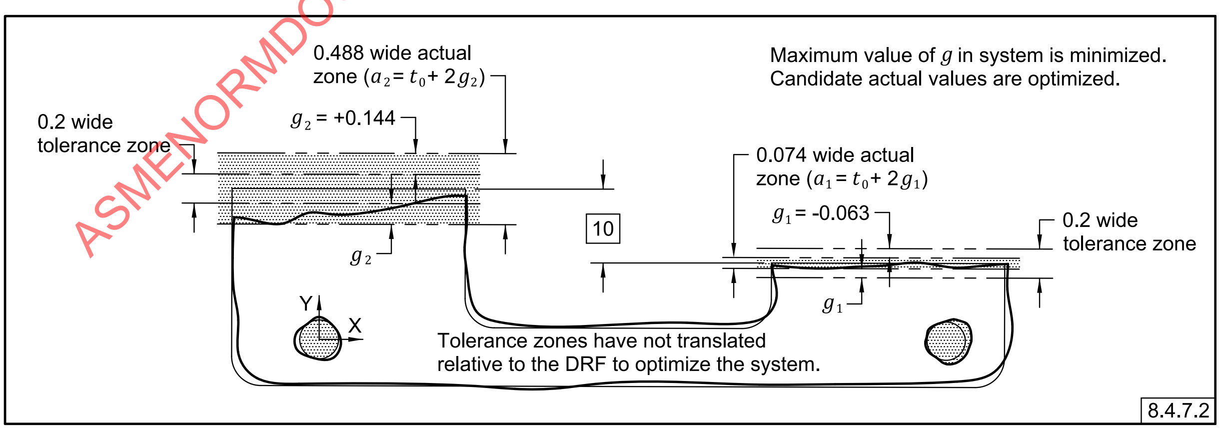


Figure 8-32 Composite Profile Lower Segment (System Optimized)

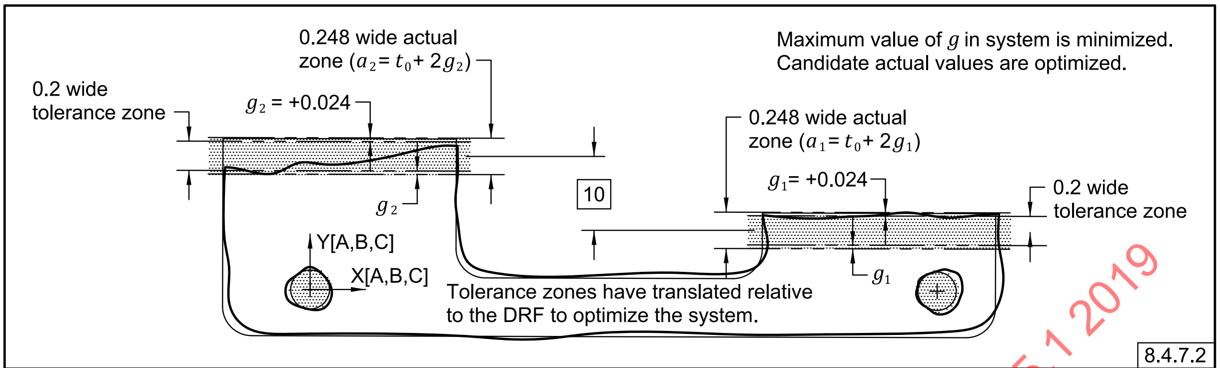


Figure 8-33 Tolerance Zone Derivation — Profile With Sharp Corner

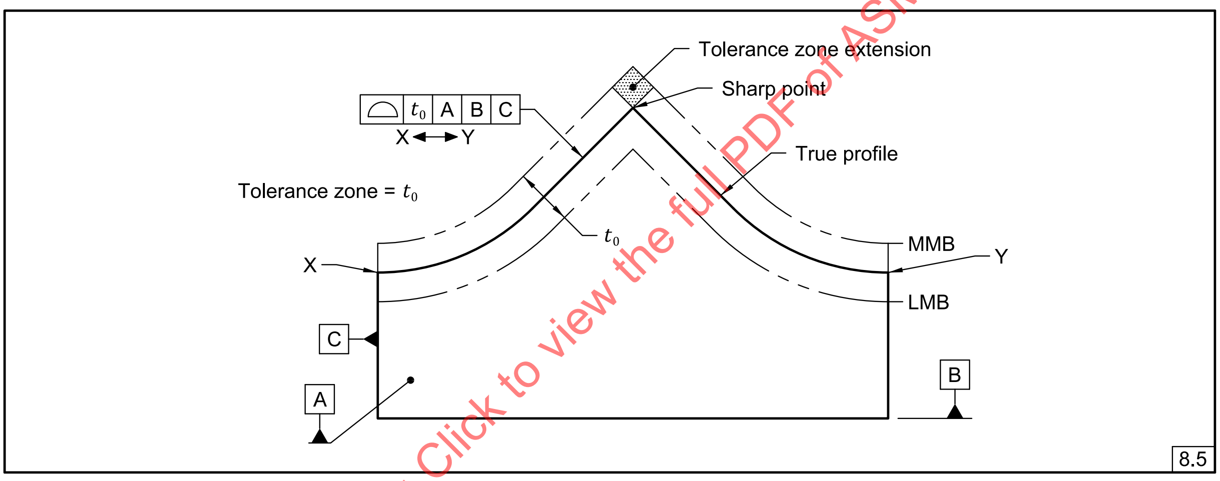
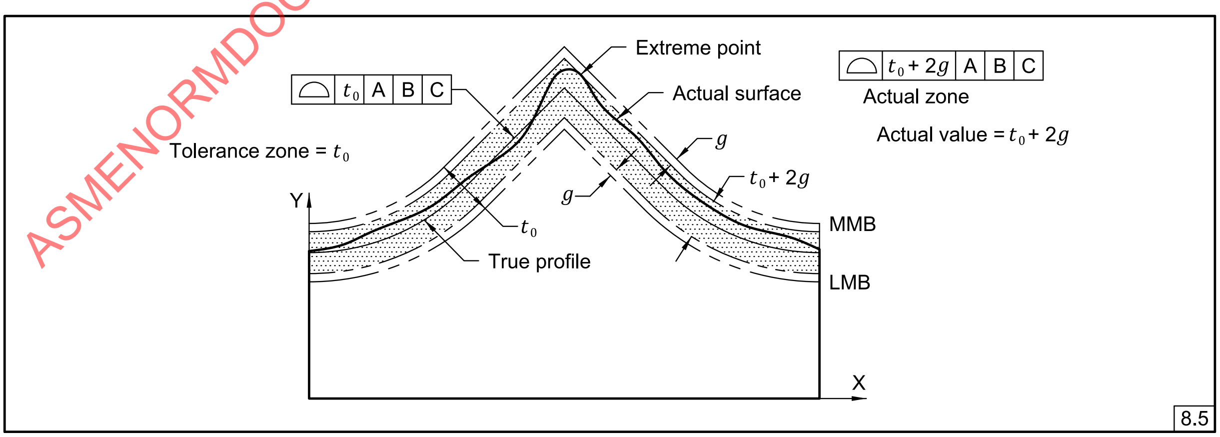


Figure 8-34 Actual Zone Definition — Profile With Sharp Corner



Section 9
Tolerances of Runout

9.1 RUNOUT TOLERANCE

Per ASME Y14.5-2009

Runout is a tolerance used to control the functional relationship of one or more features to a datum axis established from a datum feature specified at RMB. [9.2]

The types of features controlled by runout tolerances include those surfaces constructed around a datum axis and those constructed at right angles to a datum axis. [9.3]

Surfaces constructed around a datum axis are those surfaces that are either parallel to the datum axis or are at some angle other than 90 deg to the datum axis. The mathematical definition of runout is separated into two definitions: one for surfaces constructed around the datum axis, and one for surfaces constructed at right angles to the datum axis. A feature may consist of surfaces constructed both around and at right angles to the datum axis. Separate mathematical definitions describe the controls imposed by a single runout tolerance on the distinct surfaces that comprise such a feature. Circular and total runout are addressed in paras. 9.1.1 and 9.1.2, respectively.

Nominal diameters, lengths, radii, and angles establish a cross-sectional design geometry having perfect form and orientation. The design geometry may be translated axially or radially, but may not be tilted or scaled with respect to the datum axis. The tolerance band is equally disposed about this geometry and then revolved around the datum axis, a volumetric tolerance zone or an annulus-like surface of revolution is generated.

9.1.1 Circular Runout

9.1.1.1 Surfaces Constructed Normal to a Datum Axis

(a) Definition. The tolerance zone for each circular element on (contained within) a surface that is constructed at a right angle to a datum axis is generated by revolving a line segment about the datum axis. The line segment is parallel to the datum axis and is of length t_0, where t_0 is the specified tolerance. The resulting tolerance zone is the surface of a cylinder of height t_0.

For a surface point $\vec{P}_S$, a circular runout zone is the surface of a cylinder consisting of the set of points $\vec{P}$ satisfying the conditions

$$\left|\hat{D}_1 \times \left(\vec{P} - \vec{A}\right)\right| = r$$

and

$$\left|\hat{D}_1 \cdot \left(\vec{P} - \vec{B}\right)\right| \le \frac{t}{2}$$

where

$\vec{A}$ = a position vector locating the datum axis
$\vec{B}$ = a position vector locating the center of the zone
$\hat{D}_1$ = the direction vector of the datum axis
r = the radial distance from $\vec{P}_S$ to the axis
t = the size of the zone (i.e., the height of the cylindrical surface for each surface point)

(b) Conformance. The circular element through a surface point $\vec{P}_S$ conforms to the circular runout tolerance t_0 if all points of the element lie within some circular runout zone as defined above with $t = t_0$. That is, there exists $\vec{B}$ such that with $t = t_0$, all points of the surface element are within the circular runout tolerance zone.

A surface conforms to the circular runout tolerance if all circular surface elements conform.

(c) Actual Value. The actual value of circular runout for a surface that is constructed at a right angle to a datum axis is the smallest circular runout tolerance to which it will conform.

9.1.1.2 Surfaces Constructed Around a Datum Axis

(a) Definition. The tolerance zone for each circular element on a surface constructed around a datum axis is generated by revolving a line segment about the datum axis. The line segment is normal to the desired surface (i.e., the true geometric shape) and is of length t_0, where t_0 is the specified tolerance. Depending on the orientation of the feature, the resulting tolerance zone will be either a flat annular area, or the surface of a truncated cone. Mapping these two types to feature geometry, the former is associated with a right circular cylinder and the latter with a general surface of revolution.

For a surface point $\vec{P}_S$, a datum axis $\left[\vec{A}, \hat{D}_1\right]$, and a given mating surface as defined by the true geometric shape, a circular runout zone for a surface constructed around a datum axis consists of the set of points $\vec{P}$ satisfying the conditions

$$\frac{\hat{D}_1 \cdot (\vec{P} - \vec{B})}{\left|\vec{P} - \vec{B}\right|} = \hat{D}_1 \cdot \hat{N}$$

and

$$\left|\left|\vec{P} - \vec{B}\right| - d\right| \le \frac{t}{2}$$

$$\hat{N} \cdot \left(\vec{P}_S - \vec{B}\right) > 0$$

where

$\vec{A}$ = a position vector locating the datum axis

$\vec{B}$ = the point of intersection of the datum axis and the line through $\vec{P}_S$ parallel to the direction vector $\hat{N}$

$\hat{D}_1$ = the direction vector of the datum axis

d = the distance from $\vec{B}$ to the center of the zone as measured parallel to $\hat{N}$, where $d \ge t/2$

$\hat{N}$ = the surface normal at $\vec{P}_S$ determined from the mating surface as defined by the true geometric shape

t = the size of the zone as measured parallel to $\hat{N}$

Figure 9-1 illustrates a circular runout zone on a noncylindrical surface of revolution.

(b) Conformance. The circular element through a surface point $\vec{P}_S$ conforms to the circular runout tolerance t_0 for a given mating surface if all points of the circular element lie within some circular runout zone as defined above with $t = t_0$. That is, there exists d such that with $t = t_0$, all points of the circular element are within the circular runout tolerance zone.

A surface conforms to a circular runout tolerance t_0 if all circular elements of the surface conform to the circular runout tolerance for the same mating surface as defined by the true geometric shape.

(c) Actual Value. The actual value of circular runout for a surface constructed around a datum axis is the smallest circular runout tolerance to which it will conform.

9.1.2 Total Runout

9.1.2.1 Surfaces Constructed Normal to a Datum Axis

(a) Definition. A total runout tolerance for a surface constructed at right angles to a datum axis specifies that all points of the surface must lie in a tolerance zone bounded by two parallel planes perpendicular to the datum axis and separated by the specified tolerance.

For a surface constructed at right angles to a datum axis, a total runout zone is a volume consisting of the points $\vec{P}$ satisfying

$$\left|\hat{D}_1 \cdot \left(\vec{P} - \vec{B}\right)\right| \le \frac{t}{2}$$

where

$\vec{B}$ = a position vector locating the mid-plane of the zone

$\hat{D}_1$ = the direction vector of the datum axis

t = the size of the zone (the separation of the parallel planes)

(b) Conformance. A surface conforms to the total runout tolerance t_0 if all points of the surface lie within some total runout zone as defined above with $t = t_0$. That is, there exists $\vec{B}$ such that with $t = t_0$, all points of the surface are within the total runout tolerance zone.

(c) Actual Value. The actual value of total runout for a surface constructed at right angles to a datum axis is the smallest total runout tolerance to which it will conform.

9.1.2.2 Surfaces Constructed Around a Datum Axis

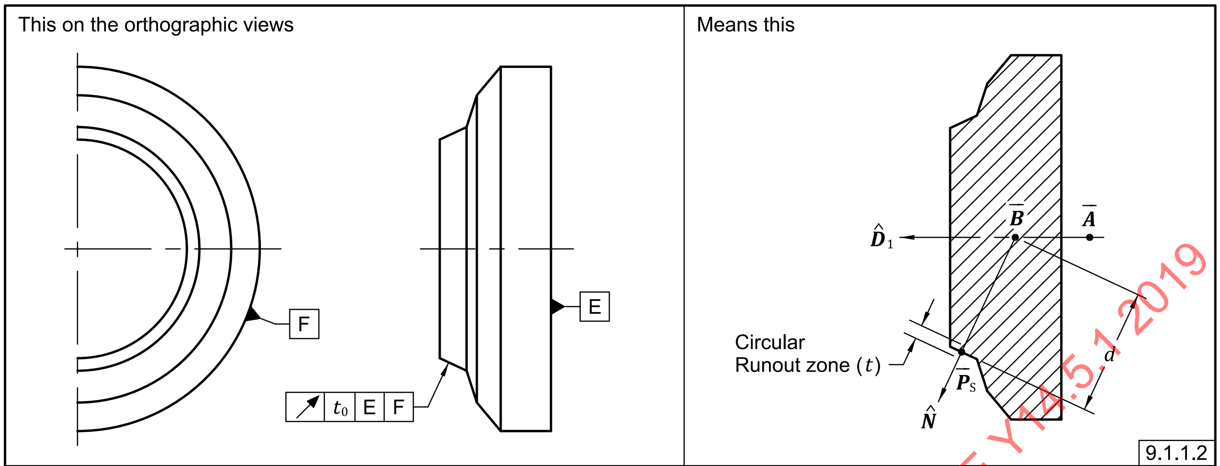
(a) Definition. A total runout tolerance zone for a surface constructed around a datum axis is a volume of revolution generated by revolving an area about the datum axis. This area is generated by moving a line segment of length t_0, where t_0 is the specified tolerance, along the desired contour as defined by the true geometric shape with the line segment kept normal to, and centered on, the desired contour (i.e., the true geometric shape) at each point. The area that is generated by sweeping the line segment along the true geometric shape is revolved about the datum axis. The resulting tolerance zone is a volume between two surfaces of revolution separated by the specified tolerance, t_0.

Given a datum axis defined by the position vector $\vec{A}$ and the direction vector $\hat{D}_1$, let $\vec{B}$ be a point on the datum axis locating one end of the desired contour as defined by the true geometric shape, and let r be the distance from the datum axis to the desired contour as defined by the true geometric shape at point $\vec{B}$. Then, for a given $\vec{B}$ and r, let $C(\vec{B}, r)$ denote the desired contour.

NOTE: Points on the desired contour as defined by the true geometric shape can be represented by $[d, r + f(d)]$, where d is the distance along the datum axis from $\vec{B}$.

For each possible $C(\vec{B}, r)$, a total runout zone is defined as the set of points $\vec{P}$ satisfying the condition

Figure 9-1 Circular Runout Zone



$$\left|\vec{P} - \vec{P}'\right| \leq \frac{t}{2}$$

where

$\vec{P}'$ = the projection of $\vec{P}$ onto the surface generated by rotating $C(\vec{B}, r)$ about the datum axis

t = the size of the zone, measured normal to the desired contour as described by the true geometric shape

(b) Conformance. A surface conforms to a total runout tolerance t_0 if all points of the surface lie within some total runout zone as defined above with $t = t_0$. That is, there exist $\vec{B}$ and r such that with $t = t_0$, all points of the surface are within the total runout tolerance zone.

(c) Actual Value. The actual value of total runout for a surface constructed around a datum axis is the smallest total runout tolerance to which it will conform.

NONMANDATORY APPENDIX A
PRINCIPAL CHANGES AND IMPROVEMENTS

A-1 GENERAL

The purpose of this Appendix is to provide users a list of the principal changes and improvements in this revision of the Standard as compared to the previous issue. The changes are summarized for each Section or Appendix in the form of additions, clarifications, extensions of principles, or resolution of differences.

A-2 STANDARD Y14 FORMAT

The format of the Standard has been revised to present the material in the sequence presented in ASME Y14.5-2009.

A-3 SECTION 1, SCOPE AND DEFINITIONS

A-3.1 Added Para. 1.2, ASME Y14 Series Conventions

Explains the ASME Y14 series conventions used in the Y14 series of standards and the conventions were applied throughout this Standard.

A-3.2 Added References

Added reference to ASME Y14.41-2012, Digital Product Definition Data Practices was added in para. 1.3.

A-3.3 New or Revised Terms and Definitions

Definitions and terms have been enhanced by expansion, addition, clarification, and reorganization.

A-4 SECTION 2, GENERAL TOLERANCING AND RELATED PRINCIPLES

A-4.1 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-4.2 Terminology

Revised in accordance with ASME Y14.5-2009

A-4.3 Added Definitions for Actual Local Size

Opposing points and circular element.

A-5 SECTION 3, SYMBOLOGY

A-5.1 No Changes to Section 3

A-6 SECTION 4, DATUM REFERENCE FRAMES

A-6.1 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-6.2 Terminology

Revised in accordance with ASME Y14.5-2009.

A-6.3 Translation Modifier

A-6.4 Tertiary Datum Simulator

Located and oriented to higher precedence datum.

A-6.5 Added New Datum Feature Types to the DOF Tables

Cone and linear extrusion.

A-6.6 Added Para. 4.7.11, Alternate Stabilization Procedures

The definition was added for a single unique datum with a constrained L2 as default.

A-7 SECTION 5, TOLERANCES OF FORM

A-7.1 Renumbered and Made Into Separate Section

Section 5 was previously Section 6 and included Orientation, Profile, and Runout

A-7.2 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-7.3 Terminology

Revised in accordance with ASME Y14.5-2009.

A-7.4 Added Definition

Derived Median Plane and Flatness

A-8 SECTION 6, TOLERANCES OF ORIENTATION

A-8.1 Renumbered and Made Into Separate Section

Section 5 was previously Section 6 and included Orientation, Profile, and Runout

A-8.2 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-8.3 Terminology

Revised in accordance with ASME Y14.5-2009.

A-9 SECTION 7, TOLERANCES OF LOCATION

A-9.1 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-9.2 Terminology

Revised in accordance with ASME Y14.5-2009.

A-10 SECTION 8, TOLERANCES OF PROFILE

A-10.1 Renumbered and Made Into Separate Section

Section 8 was previously Section 6 and included Form, Orientation, and Runout

A-10.2 Reorganization of Section

The Profile Control section from ASME Y14.5.1M-1994 was moved to Nonmandatory Appendix C, Former Practices, and replaced with new text and figures.

A-10.3 Profile Tolerance Zone Definition

A definition of a uniform profile tolerance zone was added, describing a generating line segment swept along the true profile with the disposition indicated by the specification.

A-10.4 Application of Uniform Tolerance Zones

Examples were added illustrating profile tolerance zone derivation for equally disposed, unequally disposed, unilateral inside, and unilateral outside dispositions.

A-10.5 Actual Zone Definition

A definition of an actual profile zone was added in which the generating line segment is adjusted to just envelop the actual surface.

A-10.6 Growth Parameter

The growth parameter g was introduced to represent the amount of length adjustment at each end of the line segment.

A-10.7 Relationship Between Actual Zone, Tolerance Zone, Growth Parameter, and Conformance

Ranges for the growth parameter g were summarized for conforming, nonconforming, and barely conforming conditions.

A-10.8 Actual Value Formula

A general formula was defined for the actual value of a profile tolerance for a single feature, $a = t_0 + 2g$. This formula applies to uniform profile tolerances of any disposition.

A-10.9 Application of Actual Zones

Examples were added illustrating actual zone definition for equally disposed, unequally disposed, unilateral outside, and unilateral inside dispositions. Conforming and nonconforming examples are shown.

A-10.10 New Subsection for Profile Applications

A new subsection was added to address profile applications involving multiple features, introducing the concept of a profile tolerance specification as a system that is optimized within constraints.

A-10.11 Basic Reference-Body

The new term "basic reference-body" was introduced to represent the design geometry used as the basis for profile tolerance zones.

A-10.12 Spatial Relationship

The new term "candidate spatial relationship" was introduced to generalize the Y14.5 concept of datum feature shift to apply to situations in which datum feature references are not present.

A-10.13 Tolerance Zone Transformation

The term "tolerance zone transformation" was introduced in the context of composite profile, to allow description of zones that can translate relative to the basic reference-body.

A-10.14 Candidate Configurations

The term "candidate configuration" was introduced to describe a particular state of a profile tolerance system.

A-10.15 Default Optimization Criteria

A default criteria was defined for optimization of profile tolerance systems for the calculation of actual values, which minimizes the maximum value of the growth parameter g in the system. This is a generalization of the minimum-zone criteria defined for single-feature characteristics that can be applied to multiple features and mixed tolerance values.

A-10.16 Application Examples With No Datum Reference Frame

Application of the actual zone, growth parameter, optimization, and actual value concepts were illustrated in a series of multi-figure examples. A single-feature system with no datum reference frame was explained, along with multi-feature systems with and without grouping.

A-10.17 Optimization and Actual Value Calculation Examples With Datum Reference Frames

Further multi-figure examples were added to illustrate the optimization concepts in the context of datum reference frames. Examples included a fully constrained DRF, partially constrained with simultaneous requirements, and composite profile lower segment.

A-10.18 Sharp Corners

A mathematical description was added for the extension that occurs where the true profile has a sharp corner, with figures illustrating the tolerance zone derivation and actual zone definition.

A-10.19 Nonuniform Tolerance Zone

A definition was added for conformance to a nonuniform tolerance zone.

A-11 SECTION 9, TOLERANCES OF RUNOUT

A-11.1 Renumbered and Made Into Separate Section

Section 5 was previously Section 6 and included Orientation, Profile and Runout

A-11.2 All Figures Redrawn

All figures were redrawn to show improvements for clarity and readability.

A-11.3 Terminology

Revised in accordance with ASME Y14.5-2009.

A-12 NONMANDATORY APPENDICES

A-12.1 Nonmandatory Appendix A

Nonmandatory Appendix A was added to reflect the revisions in this revision of the Standard.

A-12.2 Nonmandatory Appendix B

Nonmandatory Appendix B, "Mathematical Datum Simulators Referenced at RMB," was added to this revision.

A-12.3 Nonmandatory Appendix C

Nonmandatory Appendix C, "Former Practices," was added to this revision.

A-12.4 Nonmandatory Appendix D

Nonmandatory Appendix D, "Concepts Related to Size," was added to this revision.

A-12.5 Nonmandatory Appendix E

Nonmandatory Appendix E, "A Selection of Mathematical Concepts," was added to this revision.

A-12.6 Nonmandatory Appendix F

Nonmandatory Appendix F, "Potential Misuse of the Swept-Sphere Definition of Size," was added to this revision.

NONMANDATORY APPENDIX B MATHEMATICAL DATUM SIMULATORS REFERENCED AT RMB: DEFINITIONS AND PROPERTIES

B-1 INTRODUCTION

It is very common for tolerances to have datum features referenced at RMB. Per this Standard (see Section 4), in these scenarios a possibly-infinite set of candidate datum feature simulators is associated with the datum feature. Any of the candidate simulators may be used to evaluate the tolerances, and so the task is to identify which simulator, if any, enables the tolerances to pass.

However, in many scenarios it is desirable to specify a single datum feature simulator associated with a datum feature referenced at RMB. Having a single datum feature simulator corresponds more closely to typical mechanical techniques of evaluating tolerances. For example, a metrology engineer might place a datum plane feature on a physical datum plane simulator (surface plate), and if the part "rocks" shims would be used to stabilize the part.

Due to the desirability of a single datum feature simulator, the purpose of this Appendix is to allow design engineers to specify a well-defined single simulator associated with datum features. This Appendix provides several mathematical definitions for single simulators corresponding to datums referenced at RMB. The definitions' properties are analyzed, and a recommendation is made for which definition is likely to be the best in most cases.

B-2 REQUIREMENTS FOR A SINGLE SIMULATOR

There are several desirable attributes of a definition for a single datum feature simulator. First, the simulator must be external to the material (externality). Second, the simulator must contact the part (contact). Third, in cases where the datum feature "rocks," the solution chosen must be a single solution that minimizes the separation between the datum feature and the datum simulator (plausibility). Fourth, minute changes in the manufactured part should not correspond to large changes in the datum simulator (repeatability or stability); in other words, two similarly-manufactured parts should have similar datum simulators.

B-2.1 Concepts of Simulator Definitions

In practical datum simulator definitions, it is helpful to define the concept of signed distance. The absolute value of the signed distance is the same as normally understood distance. The sign conveys information about inside versus outside. In this document, the following convention is used: negative distances are inside the surface of the datum simulator while positive distances are outside the surface of the datum simulator. See Figure B-1, which illustrates positive and negative distances.

Using the concept of signed distance, a signed residual function $r_F(P|S)$ can be defined. That is, given a datum feature's surface F, and a candidate datum simulator S and a point P on the feature's surface F, the residual $r_F(P|S)$ is defined as the signed distance from the point P to the simulator's surface S. The first of the desired simulator attributes, the simulator being external to the material, is then equivalent to requiring the signed residuals to be positive.

B-2.2 Nonexternal Simulator Definitions

The simplest definitions for single simulators do not guarantee a simulator that is external to the datum feature. In fact, they guarantee the simulator intersects the datum feature unless the feature has perfect form. While these nonexternal definitions do not satisfy the requirements for a good simulator, they may be useful in some cases, explained below. More importantly, these nonexternal definitions are relatively simple, so they form a good base for understanding the external definitions provided later on.

B-2.2.1 Least Squares. The simplest definition for a single simulator is that of least squares (also called Gaussian). The chosen simulator is the surface S that minimizes the sum (integral) of squared distances between S and the datum feature. That is, S is the surface (e.g., plane, cylinder) that minimizes

$$\int_{P \in F} \left| r_F\left(P \middle| S\right) \right|^2 dF$$

See Figure B-2, which illustrates what a least squares simulator looks like. Two-dimensional simplifications of common feature types are shown. The least squares simulator's greatest strength is its repeatability across parts: similarly manufactured parts will almost always have highly similar datum simulators.

B-2.2.2 Min-Max. Another definition for a single simulator is known as min-max; it is also known as Chebyshev, minimax, and minimum zone. The min-max simulator surface *S* is the surface that minimizes the maximum absolute distance between *S* and the datum feature. That is, *S* minimizes

$$\max_{P \in F} |r_F(P|S)|$$

Per this definition, the worst deviation (also known as residual) is as small as possible. This property is why min-max fitting is used in many tolerance calculations (cylindricity, flatness, perpendicularity, etc.). See Figure B-3 for an illustration of min-max datum feature simulators.

B-2.2.3 L1 Minimization. The last nonexternal simulator defined in this Appendix is the L1 (or L_1 or L^1) minimization; it is also known as least absolute deviations or as minimal sum of absolute deviations. The L1 simulator is the surface *S* that minimizes the sum (integral) of the absolute distances between *S* and the datum feature. That is, *S* minimizes

$$\int_{P \in F} |r_F(P|S)| \, dF$$

The greatest strength of the L1 association is that it can ignore relatively strong aberrations relatively easily. Nicks and ridges in the surface have relatively little effect on the simulator. In a sense, the least squares simulator is a "mean" or average of the datum feature surface, while the L1 simulator is a "median" of the datum feature surface. See Figure B-4 for an illustration of L1 simulators.

B-2.2.4 Norms and Names. The name "L1" comes from the concept of *p*-norms within vector spaces, where *p* is a number between 1 and ∞. The *p*-norm $d_p(F, S)$ of the distances between a datum feature surface *F* and a simulator surface *S* is given by

$$d_p(F, S) = \sqrt[p]{\int_{P \in F} |r_F(P|S)|^p \, \mathrm{d}F}$$

Any L*p* simulator minimizes the corresponding *p*-norm of the distance between the feature surface and the simulator surface. Thus, the above definitions — least squares, min-max, and L1 minimization — can be rewritten in consistent terms, where least squares corresponds to the L2 minimization, and min-max corresponds to the L∞ minimization.

B-2.3 External Simulator Definitions

Like the simple nonexternal simulator definitions, the external simulator definitions minimize a norm. However, they utilize a progression strategy or a constraint to ensure externality.

B-2.3.1 Progression Strategies. Perhaps the simplest way to create an external simulator is to compute a simple nonexternal simulator, and allow it to progress in some way such that it becomes external. The most familiar example is sometimes known as translated least squares: a least squares plane can be translated until it is external to the material. Other kinds of progression besides translation may be desirable. For example, a least squares cylinder may grow or shrink until it is external to the material. See Figure B-5 for illustration.

It is not always desirable to progress the simulator until it is wholly external to the material. It may be beneficial to approximate how mating parts fit together. For example, a datum plane feature typically mates with a corresponding datum plane feature on another part. Typically, the peaks and valleys of one part will not perfectly line up with those of the other, allowing some nesting in the texture. This is depicted in Figure B-6. In these situations, it may be preferable to not require the datum simulator to be strictly external to the material and instead take a least squares simulator, and translate/progress it until it is mostly, but not fully, external to the material, as shown in Figure B-7.

Datum simulators chosen by progression strategies may be useful, but they are typically not plausible, in the sense that they only rarely correspond to a simulator a metrology engineer might have chosen. For example, a least squares plane that is translated to be external to the material will typically have only one point of contact with the simulator. By contrast, a metrology engineer would usually choose a simulator with two or three points of contact.

B-2.3.2 Constrained Norm-Minimizing Strategies. Another way to define an external simulator is to add constraints to the optimization problem. Any norm can be minimized, but a constraint is added such that the simulator is required to minimize the norm while being external to the material.

For example, a constrained least squares (i.e., a constrained L2) simulator can be defined as the simulator *S* that minimizes

$$\int_{P \in F} |r_F(P|S)|^2 \, \mathrm{d}F$$

subject to the constraint that the simulator lies outside the material (i.e., subject to the constraint that $r_F(P|S) \geq 0$ for every point *P* on the datum feature).

In other words, minimize the integrated squared distances, while requiring all the signed distances to be non-negative. The three main constrained simulator definitions — constrained L1, constrained L2, and