

Empowering GD&T

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Introduction

The materials contained in this document represent an effort to clarify some of the most important concepts, tools and rules found in the ASME Y14.5 2009 Standard, as well as cast light on certain processes and best practices in order to help users apply GD&T more effectively and with greater ease. Mastering GD&T to apply it functionally and effectively is expensive, requiring time and dedication, but its costs are insignificant compared to the cost of the confusion and waste caused by “bad” GD&T or “no” GD&T. Given that the difficulty of “getting it right” often inclines users to see the acronym “GD&T” as standing for **(G)**rim, **(D)**epressing & **(T)**roublesome, it would seem high time to turn it into something **(G)**rand, **(D)**elightful & **(T)**antalizing instead. Let us hope that what follows helps.

The material presented below includes no quotes from the Standard itself, but does refer to the equivalent materials by indicating paragraph numbers and pages where they can be found. The idea is to restate the original material in ways to make it more understandable and on occasion to point out recommended changes to clarify and enhance the power of GD&T.

1. Concepts

Fully grasping the fundamental concepts of GD&T is essential in order to use it effectively. For example, failure to understand the difference between a Datum and a Datum Feature is extremely common, leading many users to believe that the letters which appear in the last compartments of a Feature Control Frame represent Datums, not Datum Features, which of course is impossible, given that we can't simulate a Datum at its Maximum Material Boundary because it has no material. Furthermore, failure to understand that a Datum Reference Frame is not a collection of Datums, but in fact a Cartesian coordinate system merely constrained by a set of Datums, leads to further confusion. The following paragraphs represent efforts to come up with refined definitions of the listed concepts to hopefully enable their more effective use, and include references to the Y14.5 2009 Standard definitions for comparison purposes.

- 1.1 Basic Dimensions
- 1.2 Datum Features
- 1.3 Datum Targets
- 1.4 Datum Feature Simulators
- 1.5 Datums
- 1.6 Datum Reference Frames
- 1.7 Tolerance Zones
- 1.8 Tolerance Zone Mobility
- 1.9 Material Condition & Material Boundary Modifiers
- 1.10 Virtual Maximum Material Boundary

1.1 Basic Dimensions:

Basic dimensions are fixed (invariant) angular, linear and radial dimensions extracted from 3D CAD models which serve to orient and locate tolerance zones relative to one another and relative to Datum Reference Frames. Basic dimensions are specified in rectangular frames. Basic dimensions also serve to orient and locate Datum Targets relative to the Datum Reference Frames they help to establish. (Y14.5 2009 §1.3.23 p.3)

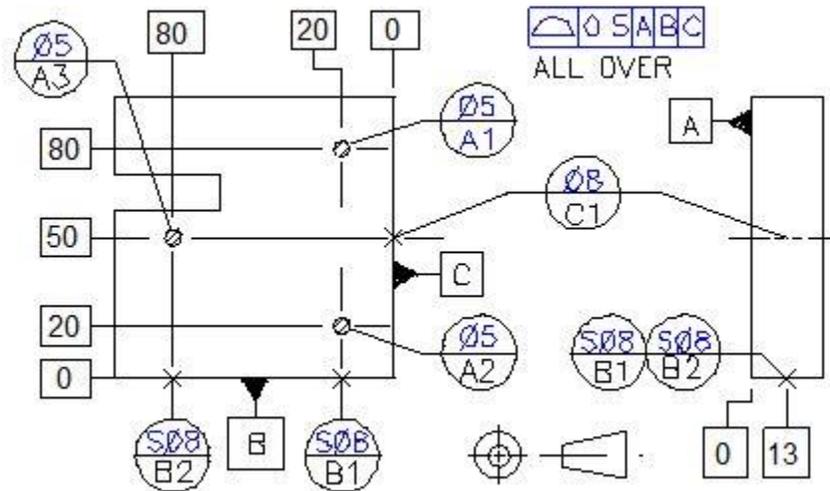
1.2 Datum Features:

Datum Features are specially labeled, imperfect, physical surfaces of real parts which 1) serve to constrain rotational and translational degrees of freedom during assembly processes, and 2), when listed in Feature Control Frames, represent a set of instructions for establishing Datum Reference Frames. (Y14.5 2009 §1.3.16 p.3).

1.3 Datum Targets:

Datum Targets are limited portions of Datum Features in the form of points, lines or areas, which represent those portions of the feature which the mating Datum Feature engages during assembly. As shown in the figure below, Datum Targets must be oriented and located by Basic dimensions relative to the DRF they define. Datum Targets are specified using Datum Target Labels whose lower segments contain the name of the target and whose upper segments remain empty in the case of point and line Datum Targets (note: but should contain the diameter of the spherical or cylindrical simulator), and in the case of circular or square area Datum Targets, contain the diameter or edge length of the area simulator. Datum Targets are referenced in Feature Control Frames using the names of their defining Datum Features. (Y14.5 2009 §1.3.20 p.3 + §4.24 p.83)

Best Practices: Datum Targets shall always be used when a Datum Feature is only partially engaged by its mating Datum Feature. (Y14.5 2009 (§4.24 p83)



1.4 Datum Feature Simulators:

A Datum Feature (or Datum Target) Simulator is a perfect imaginary, or almost perfect real, inverse Datum Feature representing the mating Datum Feature, which serves as a bridge from the imperfect real world of Datum Features to the perfect imaginary world of Datum Reference Frames, and

- 1) from which we extract Datums,
- 2) in which we first establish Datum Reference Frames, and
- 3) with which we transfer Datum Reference Frames to actual parts.

(Y14.5 2009 §1.3.17.1 and §1.3.17.2 p.3)

Notes:

- 1) **Datum Feature Simulator Behavior:** The geometry and behavior of Datum Feature Simulators are

determined 1) by the geometry of their defining Datum Features, 2) by the controls imposed on their defining Datum Features, 3) by their associated Material Boundary modifiers (S), (M) or (L), and 4) by “The Rules of Datum Feature Simulator Management”.

Examples: 1) The Material Boundary modifier (S) requires the Datum Feature Simulator to expand or contract toward the in-space surface of the associated Datum Feature and achieve stability relative to it. 2. The modifier (M) requires the Simulator to be fixed in size at the Virtual Maximum Material Boundary of the defining Datum Feature in order to permit taking advantage of potential residual “in-space” play between mating parts. 3. The modifier (L) requires the Simulator to be fixed in size at the Virtual Least Material Boundary of the defining Datum Feature to permit taking advantage of potential residual material in a machining operation. See the entry “Rules of Datum Feature Simulator Management” on p. 10 for more details.

- 2) Examples of Real Datum Feature Simulators 1) the Datum Reference Frame establishing components of a “hard gage”, and 2) the part constraining features of a “manufacturing fixture”.

For further insights into Datum Features, Datum Feature Simulators and Datums, see the following table. See also “The Rules of Datum Feature Simulator Management” (p.10) “The Rules of Natural Datum Reference Frame Establishment” (p.9), the “Feature Control Frame Decoding Process” (p.15) and “The Datum Reference Frame Establishment Process” illustration (p.16).

1.5 Datums:

Datums are the minimum, mutually embedded set of a single, perfect imaginary point, and/or straight line (axis), and/or plane, which together fully characterize the orientation and location of a Datum Feature Simulator, or the orientation and location constraining impact of a Datum Target Simulator. Datums serve to impose constraints on “starter” coordinate systems, and turn them into Datum Reference Frames. (Y14.5 2009 (§1.3.13 p.3) Note: There are six possible Datums:



Note: For more insights into Datums, see the “Datum Reference Frame Establishment Process” illustration at the end of the document.

1.6 Datum Reference Frames:

A Datum Reference Frame (DRF) is a Cartesian (or cylindrical, or spherical) coordinate system constrained by a set of Datums extracted from a set of Datum Feature Simulators, defined by a set of Datum Features listed in a Feature Control Frame. Datum Reference Frames serve, with the help of Basic dimensions, to orient and locate Tolerance Zones and Datum Targets. (Y14.5 2009 definition §4.1 p.48).

Notes: In the absence of any Datum Feature references, the DRF and its associated tolerance zones are a “super mobile” set. In the presence of Datum Feature references which constrain between one and five degrees of freedom, the DRF and its associated tolerance zones are a “residually mobile” set, and in the presence of Datum Feature references which constrain all six degrees of freedom, the DRF and its associated tolerance zones are stable, except in the presence of the Material Boundary modifiers (M) or (L), when they are again residually mobile.

Notes:

- 1) Datum Feature Simulator Behavior: The geometry and behavior of Datum Feature Simulators are determined 1) by the geometry of their defining Datum Features, 2) by the controls imposed on their defining Datum Features, 3) by their associated Material Boundary modifiers (S), (M) or (L), and 4) by “The Rules of Datum Feature Simulator Management”.

Examples: 1) The Material Boundary modifier (S) requires the Datum Feature Simulator to expand or contract toward the in-space surface of the associated Datum Feature and achieve stability relative to it. 2) The modifier (M) requires the Simulator to be fixed in size at the Virtual Maximum Material Boundary of the defining Datum Feature in order to permit taking advantage of potential residual “in-space” play between mating parts. 3) The modifier (L) requires the Simulator to be fixed in size at the Virtual Least Material Boundary of the defining Datum Feature to permit taking advantage of potential residual material in a machining operation. See the entry “Rules of Datum Feature Simulator Management” on p. 10 for more details.

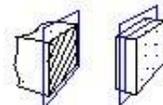
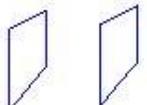
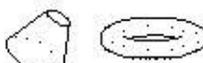
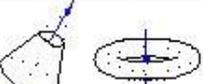
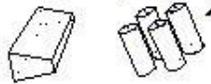
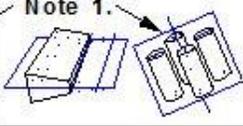
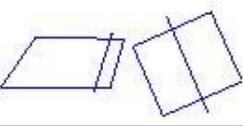
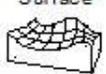
- 2) Examples of Real Datum Feature Simulators 1) the Datum Reference Frame establishing components of a “hard gage”, and 2) the part constraining features of a “manufacturing fixture”.

Datum Feature Simulators, Datums & Degrees Freedom

Datum Feature Simulators are “perfect” inverse Datum Features. A Datum is the minimum set of one perfect imaginary point, and/or line, and /or plane, which together, fully characterizes the orientation and location of a Datum Feature Simulator. Datums serve to constrain the rotational and translational degrees of freedom of starter coordinate systems and thus to establish DRFs.

Note 2.

Degrees of Constraint Capability		
Pitch Yaw	Roll	Translation

Datum Feature Simulator	DFS + Datum	Datum	Datum Type	Rx	Ry	Rz	Tx	Ty	Tz
Sphere 			Point	—	—	—	✓	✓	✓
Cylinder 			Line	✓	✓	—	✓	✓	—
Planar Surface Slab 			Plane	✓	✓	—	—	—	✓
Cone Torus 			Point on-Line	✓	✓	—	✓	✓	✓
Wedge Cyl. Pattern 	Note 1. 		Line in-Plane	✓	✓	✓	✓	✓	—
Compound Curved Surface 			Point on-Line in-Plane	✓	✓	✓	✓	✓	✓

Note 1.: This is a Composite Datum Feature Simulator, for which the indicated line-in-plane Datum is only one of at least 14 possible line-in-plane Datums which could be defined.

Note 2.: The universal concepts of Pitch, Yaw and Roll are not tied to the specific rotational degrees of freedom Rx, Ry, and Rz. Thus, bearing only the Right Thumb Rule in mind, the X, Y and Z axes of a Datum Reference Frame may be named in any way considered most useful for communicating design intent.

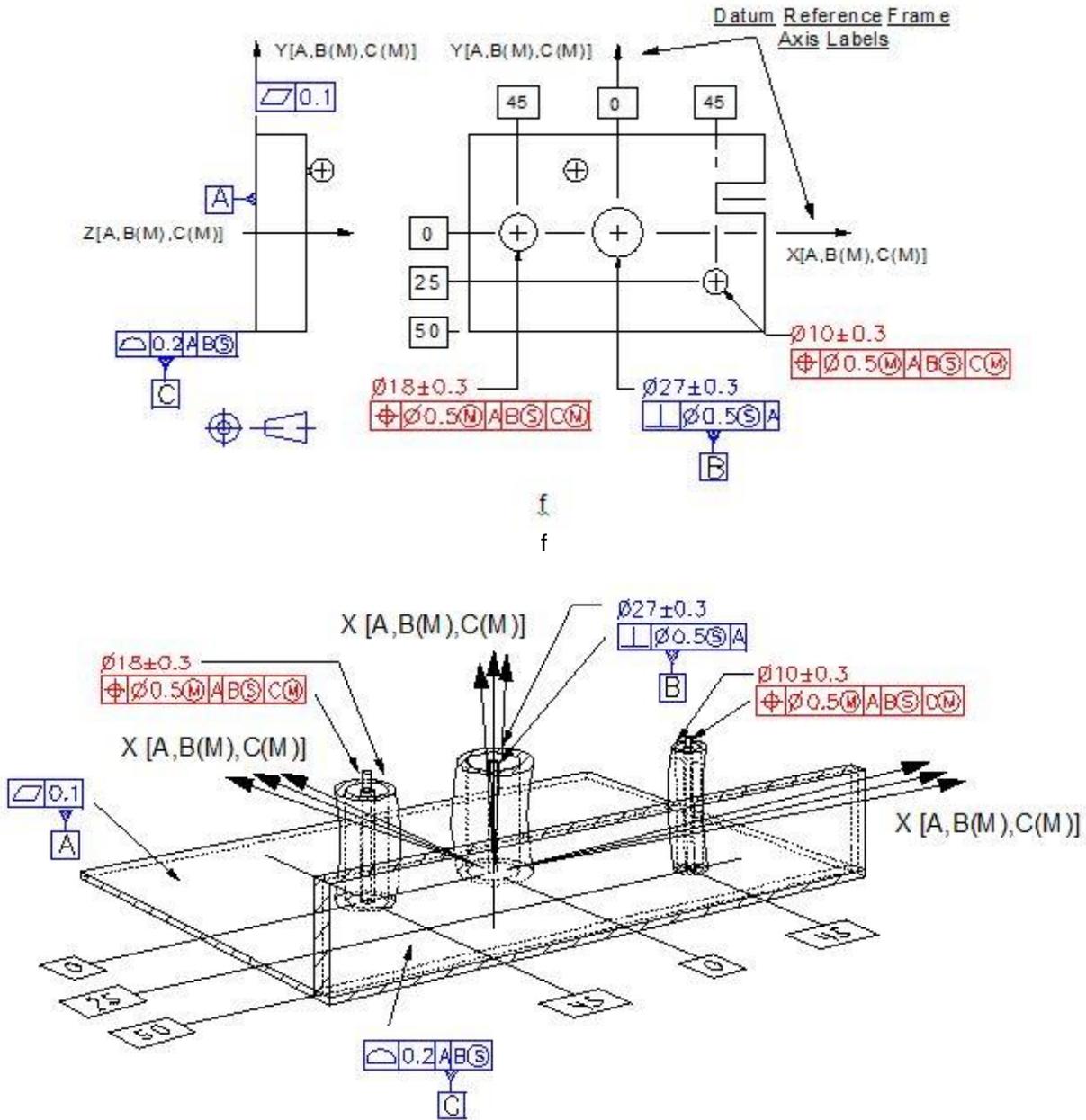
For further insights into Datum Features, Datum Feature Simulators and Datums, see the following table. See also “The Rules of Datum Feature Simulator Management” (p.10) “The Rules of Natural Datum Reference Frame Establishment” (p.9), the “Feature Control Frame Decoding Process” (p.15) and “The Datum Reference Frame Establishment Process” illustration (p.16).

1.7 Tolerance Zones:

A tolerance zone is a perfect imaginary, bounded region of space specified by a Geometry Control Tool (Ø, Position, Surface Profile, Total Runout, Cylindricity), within which a specific component of the controlled

feature is required to lie. Tolerance zones are generally normal expansions of the controlled Component of the feature, namely 1) a tube-like zone in the case of a cylindrical surface controlled by the Diameter tool, 2) a cylindrical zone in the case of the axis of a bore controlled by the Position tool, and 3) a spherical skin-like zone in the case of a sphere controlled by the Surface Profile tool. Tolerance zones defined by location and/or orientation constraining tools are oriented and located by Basic dimensions relative to one another and relative to their associated Datum Reference Frames. Tolerance zones defined by size and form tools are orientation and location unconstrained.

Examples: The tolerance zone defined by the Flatness tool is “slab-like”, by the \varnothing tool is “tube-like”, by the Surface Profile tool applied to a planar surface is “flat skin-like”, by the Position tool applied to a bore is cylindrical, and although not shown, by the Circular Runout tool applied to a shaft is “circular ribbon-like”,



Part Drawing and Resulting, Residually Mobile Tolerance Zones

1.8 Tolerance Zone Mobility – The Concept of Simultaneous Requirements:

When mating parts are assembled they generally experience residual play, namely are free to shift slightly relative to one another before fasteners are tightened. It is natural for the assembly crew to take advantage of such residual play in order to hopefully make “everything fit”, but it is quite possible that a shift in one direction will enable one feature to mate, but not another, and a shift in another direction enable the second to mate, but no longer the first. However, if both sets of features meet their requirements “simultaneously”, all is well.

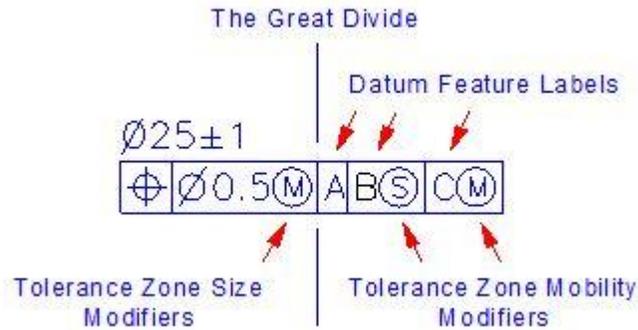
Given the part shown in the illustration above, Datum Features A, B and C establish the Datum Reference Frame (DRF) illustrated in both figures, which is potentially residually “pitch” & “yaw” and “roll” mobile, namely “pitch” & “yaw” mobile due to the impact of the Rule of Rocking & Rolling Datum Feature Simulation (§3.3.5) and residually “roll” mobile due to the impact of the Material Boundary (Tolerance Zone Mobility) modifier (M) associated with Datum Feature C.

When grouped using the nX, All Around or other grouping tools, a set of tolerance zones imposed by a Geometry Control Tool such as Position or Surface Profile makes up a local simultaneous set, namely the zones are fixed in orientation and location relative to one another regardless of their potential mobility as a group. In the absence of fully constraining Datum Feature references, the local simultaneous set becomes residually mobile as a group. If a collection of Feature Control Frames defining multiple local sets of tolerance zones reference the same Datum Features in the same order with the same Material Boundary (Tolerance Zone Mobility) modifiers (S), (M) or (L), but fail to fully constrain all six degrees of freedom, they define a residually mobile, global simultaneous set.

In greater detail, under the impact of grouping tools and the Position and Surface Profile tools, Basic dimensions orient and locate individual tolerance zones relative to one another and under the impact of Datum Features, relative to Datum Reference Frames. In the absence of any Datum Feature references, the Datum Reference Frame is “super mobile” as are the associated tolerance zones as a group. In the presence of Datum Features which fail to constrain all six degrees of freedom, the Datum Reference Frame is “partially mobile” as are the associated tolerance zone groups. Given Datum Features which constrain all six degrees of freedom, the Datum Reference Frame is “stable”, except in the presence of the Material Boundary (Tolerance Zone Mobility) modifiers (M) or (L), in which case the Datum Reference Frame and its associated tolerance zones are “residually mobile”. As set forth in greater detail in §1.9, the Material Boundary (Tolerance Zone Mobility) modifier (S) forbids the machine shop and the QA department from taking advantage of any potential residual mobility, the Material Boundary (Tolerance Zone Mobility) modifier (M) permits taking advantage of potential residual “in-space” play between mating parts during assembly, and the modifier (L) permits taking advantage of potential residual material during material removal processes.

1.9 Material Condition & Material Boundary Modifiers (“Tolerance Zone Size” & “Tolerance Zone Mobility” Modifiers):

The modifiers (S), (M) and (L) come in two groups: 1) those associated with tolerance values, and 2) those associated with Datum Feature labels. In case 1), the Standard refers to them as “material condition” modifiers, and in case 2) as “material boundary” modifiers (See Y14.5 2009 definitions §1.3.38 and §1.3.39 p.6 and §1.3.48 and §1.3.49 p.7). This nomenclature however, fails to communicate their actual functions, and therefore causes confusion among users leaving them little choice but to “interpret” callouts based on tribal understandings. The following alternative nomenclature is therefore recommended, namely to replace the term “Material Condition” modifiers with the term 1) Tolerance Zone Size (TZS) modifiers, and the term “Material Boundary” modifiers with the term 2) Tolerance Zone Mobility (TZM) modifiers, as illustrated in the figure below.



Namely, Tolerance Zone Size (TZS) modifiers impact the size of tolerance zones, and Tolerance Zone Mobility (TZM) modifiers impact the mobility of tolerance zones by impacting the mobility of Datum Reference Frames. Decoding the above Feature Control Frame makes this abundantly clear:

“Position requires the bounded axis of the “bore” to lie within a cylindrical tolerance zone of diameter 0.5 mm at MMC, expanding by as much as 2 mm as the bore departs from MMC toward LMC, which is oriented and located by Basic dimensions relative to a Datum Reference Frame established using Datum Feature A simulated “we don’t know how” (due to lack of an explicit modifier), Datum Feature B simulated (S)tably, regardless of its Material Boundary, and Datum Feature C simulated (M)obly at its Virtual Maximum Material Boundary.

In addition to encouraging use of these new names, the following paragraphs set forth additional important ideas.

Comments:

1. Unfortunately, the Y14.5 2009 Standard forbids explicit use of the modifier (S), namely users have to remember that in certain cases the modifier (S) is actually hiding behind a tolerance value or a Datum Feature label and realize that it might be more functionally replaced by an (M) or an (L). Explicit use is strongly recommended, and can be made legal with a drawing note.
2. Unfortunately there are no rules in the Y14.5 2009 Standard helping users determine when TZS (Tolerance Zone Size) and TZM (Tolerance Zone Mobility) modifiers are applicable and therefore when the (S) is present by default. Here are the missing rules (also presented in the Rules section as rules 6. and 7.):
 - a. Rule of TZS modifier applicability: TZS modifiers apply only when the controlled feature component is a “symmetry” component, namely a center point, an axis, a median line, a mid-plane or a median plane.
 - b. Rule of TZM modifier applicability: TZM modifiers apply to all Datum Feature types except non-location constrained planar Datum Feature (example: a primary planar Datum Feaure).
3. Although forbidden by the Y14.5 2009 standard, in order to be fully functional, TZM modifiers should apply to all Datum Feature types, including non-location constrained planar Datum Features, with (S) imposing (S)tability in-space, (M) permitting residual (M)obility (“rocking” and “rolling”) in-space, and (L) permitting residual (L)ability (“rocking” and “rolling”) in-material.
4. Note: Because the Standard fails to enable use of TZM modifiers on non-location constrained planar Datum Features, making “mobility” in space the only option by default, users are encouraged to use drawing notes to impose stability in functional ways. This could be done by requiring the Datum Feature Simulator to be an inverse planar surface stabilized by a force vector passing through the centroid or an explicitly specified point on the Datum Feature. See the Rule of Rocking & Rolling Datum Feature Simulation for further insights

5. Unfortunately there are no guidelines in the Y14.5 2009 Standard setting forth the functions which the various TZS and TZM modifiers encode, so here they are:

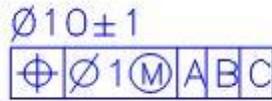
<u>Tolerance Zone Size Modifiers</u>	<u>Tolerance Zone Mobility Modifiers</u>
<p>(S) encodes the “aiming” or “centering” function of a feature and causes the tolerance to be (S)tuck at the specified value. The modifier (S) properly encodes the function of threaded features, for which the tolerance value is naturally stuck at the specified value. <u>Note:</u> To maximize the functionality of the TZS modifier (S), it should really be renamed (SM) to specify its applicability “in-space”, and be extended to include (SL), to specify its applicability “in-material”.</p>	<p>(S) encodes the in-space “aiming” or “centering” function and requires the referenced Datum Feature to be simulated (S)tably in space, namely requires the simulator to expand or contract to consume all the available space in or outside the defining Datum Feature to achieve Datum Reference Frame stability. <u>Example:</u> The TZM modifier (S) properly encodes the stabilizing impact of threaded Datum Features, which naturally impose stability during assembly. <u>Recommendation:</u> To maximize the functionality of the TZM modifier (S), it should really be renamed (SM) to specify its application “in-space”, and be extended to include (SL), to specify its application “in-material”.</p>
<p>(M) encodes the “clearance” function and provides (M)ore tolerance as the controlled feature departs from MMC toward LMC.</p>	<p>(M) encodes the in-space “play” function and requires the referenced Datum Feature to be simulated (M)obly in space, namely requires the simulator to be fixed in size at the Virtual Maximum Material Boundary of the defining Datum Feature, enabling Mfg. and QA to take advantage of residual in-space mobility during assembly.</p>
<p>(L) encodes the “interference” or “overlap” function and provides (L)ots of additional tolerance as the controlled feature departs from LMC toward MMC.</p>	<p>(L) encodes the in-material “play” function and requires the referenced Datum Feature to be simulated (L)ably (i.e. unstably) in the material, namely requires the simulator to be fixed in size at the Virtual Least Material Boundary of the defining Datum Feature, and enables Mfg. and QA to take advantage of residual in-space mobility during assembly, enabling Mfg. and QA to take advantage of residual in-material “lability” during manufacturing.</p>

1.10 The Virtual Condition:

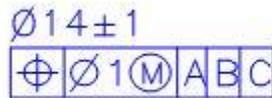
Under the impact of the Material Condition (Tolerance Zone Size) modifiers (S) or (M), the Virtual Condition of a feature is a fixed, in-space boundary generated by the collective effects of all the imposed controls. Under the impact of the Material Condition (Tolerance Zone Size) modifier (L), the Virtual Condition of a feature is a fixed, in-material boundary. The Virtual Condition forms the basis for selecting the controls to be imposed on the mating feature to guarantee assembly. (Y14.5 2009 (§1.3.67 p.7).

Example 1 A free standing shaft with the control $\varnothing 10 \pm 1$. In the absence of location and/or orientation constraints, and as a result of the Envelope Rule, the worst case size for assembly is the feature’s in-space Virtual Condition = $\varnothing 11$. In order to guarantee assembly, the mating unconstrained bore must have the same in-space Virtual Condition, leading to the control $\varnothing 12 \pm 1$.

Example 2: A location constrained shaft with the controls



In the presence of location constraints, and as a result of the explicit modifier (M), the Virtual Condition is determined by the feature's MMC size = Ø11, plus the impact of permissible offsets and tilts at MMC, namely the Position tolerance of 1, producing a maximum, Virtual MMB of Ø12. In order to guarantee assembly, the mating bore must have the same minimum Virtual MMB, leading to the control



2 Geometry Control Tools

2.1 Overview

There are only four things that can go wrong with the geometry of machine parts: 1) size, 2) form (including finish), 3) orientation and 4) location. There are also four sets of “tools” with which to impose constraints on what can go wrong. The following charts list all the truly functional tools in the Y14.5 2009 set, and include their names, their symbols, and the feature components they control. Geometry Control Tools impose limits on errors in size, form, orientation and location by requiring said components to lie inside appropriate tolerance zones. Feature components include the entire surfaces of features, the axes, median lines, circular and straight line surface elements of cylindrical features, the center points and circular line elements of spheres, the mid-planes and median planes of slabs and slots, etc.

Size Tools

These Tolerance Zones may be neither Oriented nor Located by Basic Dimensions

Geometry Control Tool		Controlled Feature Components
∅	Diameter	Entire Surface
	Thickness (Width)	Entire Surfaces
S∅	Spherical Diameter	Entire Surface
	Surface Profile	Entire Surface
R	Radius (Classical)	Circular Surface Lines
SR	Spherical Radius	Entire Surface

Form Tools

These Tolerance Zones may be neither Oriented nor Located by Basic Dimensions

Geometry Control Tool		Controlled Feature Components
	Flatness	Entire Surface
	Flatness	Median Plane
	Cylindricity	Entire Surface
	Circularity	Circular Surface Lines
	Surface Line Straightness	Straight Surface Lines
	Median Line Straightness	Median Line

Orientation Tools

These Tolerance Zones can only be Oriented, not Located, by Basic Dimensions

Geometry Control Tool		Controlled Feature Components
	Angularity	Planar Surfaces Mid-Planes Axes Straight Surface Lines
	Parallelism	
	Perpendicularity	

Location Tools

These Tolerance Zones can be both Oriented and Located by Basic Dimensions

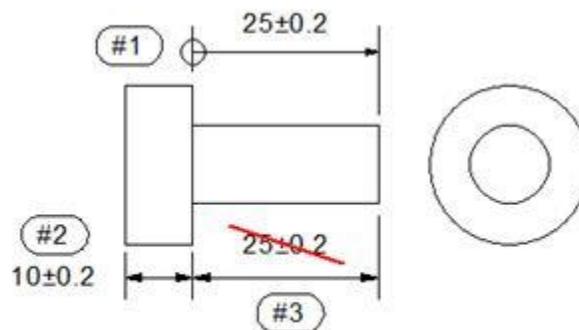
Geometry Control Tool		Controlled Feature Components
	Surface Profile	General Surfaces
	Position	Axes
	Position	Mid-Planes
	Position	Center-Points
	Circular Runout	Circular Line Elements
	Total Runout	Surfaces of Revolution

These Tolerance Zones can only be Located by Toleranced Nominal Dimensions

Geometry Control Tool		Controlled Feature Components
	Dimension Origin	Planar Surfaces

2.2 The Dimension Origin Tool:

The last tool in the list is a very important, widely unknown tool – a generalized version of the depth tool – which uses toleranced nominal dimensions to locate planar surfaces. In contrast to the Width tool shown properly used in item #2 and misused in item #3 in the figure below, the Dimension Origin tool, shown as item #1, clearly differentiates between the controlled and the reference feature and is the only tool (other than Surface Profile) with which to control the distance between planar surfaces whose normal vectors point in the same direction, namely don't form "features of size".



The "No-Name" Datum Feature Label

Some Y14.5 2009 Standard defined tools can and should be left in the box, because they impose non-functional constraints or constraints which other tools can impose more functionally. Here they are followed by descriptions and the reasons for discouraging their use:

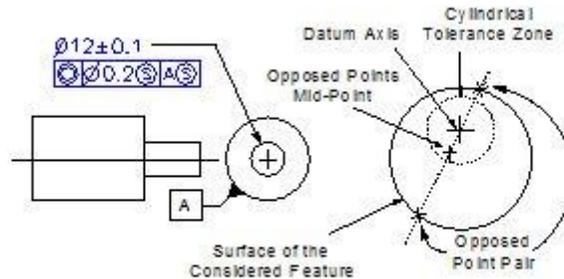
Discouraged Tools

These Tools are discouraged

Geometry Control Tool	Controlled Feature	Components
	Concentricity	Opposed Pt Mid-Points
	Symmetry	Median Planes
	Line Profile	Curved Surface Lines
CR	Controlled Radius	Fillet

2.3 The Concentricity Tool (Y14.5 2009 §7.6.4 p.153)

Use & Limitations: The Concentricity tool is commonly understood to require the axis of a surface of revolution to lie within a cylindrical tolerance zone, but in fact applies to the midpoints of all opposed point pairs formed by intersecting the surface of the Considered Feature with lines which are normal to and pass through the Datum axis. Because this Y14.5 tool 1) fails to address the Axis of the Considered Feature, 2) therefore cannot be applied to threaded features, 3) is sensitive to, but does not reliably control Circularity or Cylindricity, 4) does not permit use of the Material Condition and Material Boundary modifiers (M) and (L), 5) poses substantial difficulties for coordinate metrology software, and 6) can be replaced by the far more effective tool, Position, to control coaxiality, it is essentially worthless and should never be used. Note: The RFS modifier (S) is shown explicitly for clarity, even though not allowed in Y14.5 2009.



Concentricity Tolerance Zone

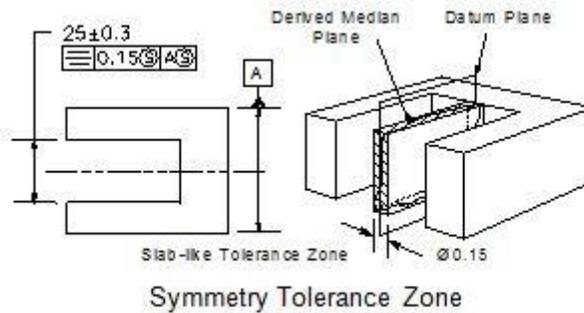
Concentricity Tolerance Zone

Replacement Tools: The following tools should be used in place of Concentricity and are listed in the order of their closest functional similarity: 1) Position, 2) Circular Runout, 3) Total Runout and 4) Surface Profile (the “everything” tool).

2.4 The Symmetry Tool (Y14.5 2009 §7.7.2 p.156)

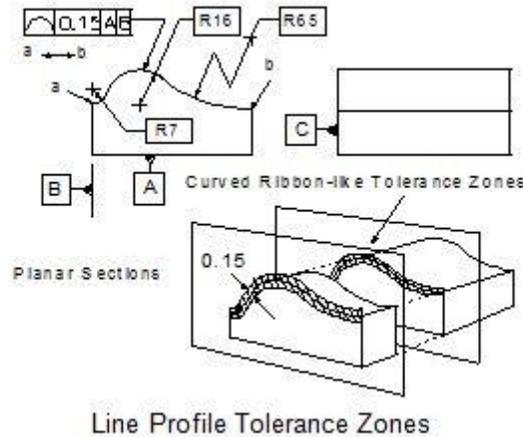
Use & Limitations: The Symmetry tool applies exclusively to the Median Planes of slabs and slots, and requires them to lie within a slab-like tolerance zone whose mid-plane coincides with the referenced Datum Plane. Because the Position Tool 1) provides equally functional control, 2) applies to Mid-Planes rather than to Median Planes, and 3) allows the use of the Modifiers (M) and (L), its use is strongly recommended in place of the Symmetry Tool.

Replacement Tools: The tools which should be used in place of Symmetry are, in the order of their closest functional similarity: 1) Position, and 2) Surface Profile (the “everything” tool).



2.5 The Line Profile Tool (Y14.5 2009 §8.2.1.2 p.158)

Use & Limitations: The Line Profile tool is identical in capability to the Surface Profile tool, but replaces its skin-like zone with stacks of twisting ribbon-like zones which make up a simultaneous set and are required to be everywhere normal to the Basic surface of the Considered Feature. The lack of any functional difference between it and the Surface Profile tool, added to the complexity which twisting ribbon-like tolerance zones pose for metrology, plus the difficulty of specifying how the zones are to be oriented and aligned, makes the Line Profile tool essentially useless.



Note: The Line Profile example given in Y14.5 2009 Fig. 8-27 p.179 is 1) illegal, due to the fact that only Basic dimensions may constrain the location of Profile tolerance zones, and 2) even if up-down mobility were permissible, the entire set of ribbon-like tolerance zones makes up a simultaneous set by default, imposing a global Parallelism control on the entire surface rather than on each individual line. Furthermore, the intended control can be properly implemented using the Parallelism tool with a subordinate note: EACH LINE ELEMENT.

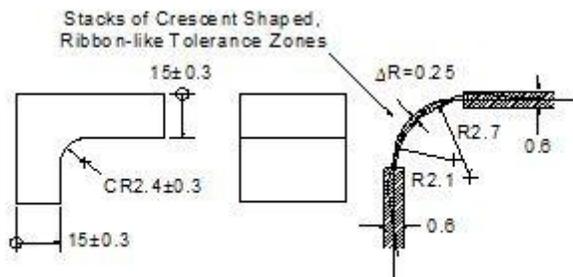
2.6 The Radius Tool (Y14.5 2009 §2.15.1 p.36)

Use & Limitations: The Y14.5 Radius Tool defines a largely non-functional, crescent shaped, ribbon-like, tolerance zone with a maximum width reduced to 41% of the stated tolerance at its center and reduced to zero at its ends (See the illustration for Controlled Radius here below).

Replacement Tool: It is recommended that the Y14.5 defined Radius tool be replaced by the “classical” Radius tool "R" whose tolerance zone is defined by two concentric circles with radii equal to the upper and lower limits specified by the call-out, for example 4 ± 0.3 .

2.7 The Controlled Radius Tool (Y14.5 2009 §2.15.2 p. 36)

Use & Limitations: The Controlled Radius Tool is identical in effect to the Y14.5 defined Radius Tool, except that it requires a "fair curve without reversals". This tool has the same faults as the Y14.5 defined Radius tool, in that it defines a ribbon-like tolerance zone of width zero at its extremities, and is further complicated by the highly interpretable requirement of "a fair curve without reversals".



"Controlled Radius" Tolerance Zone

Replacement Tool: It is recommended that the Controlled Radius tool always be replaced by the "classical" Radius tool "R" defining a tolerance zone of constant width.

3. Rules

Without rules, GD&T can only be used to "decorate" drawings and CAD models, making it open to "interpretation" and therefore not only worthless, but also dangerous, namely open to different interpretations by different individuals. Because so much GD&T is largely "decorative" and is understood to be open to "interpretation", machine shops must charge more for GD&T specified parts in order to cover the cost of confusion, namely of actually determining and meeting the client's actual objectives. In spite of the huge importance of rules with which to enable unique "encoding" and "decoding" of GD&T, with the exception of the small set found in Y14.5 2009 §1.4 (p.7), most Y14.5 statements which represent rules are identified as mere "principles", are not given names, and cannot be found in the index. Here is a small sample of important GD&T rules, some set forth, but many merely hinted at in the Standard, which are presented in fresh terms to hopefully enable their clear understanding and effective use.

- 3.1 The Envelope Rule
- 3.2 Rules of Natural Datum Reference Frame Establishment
- 3.3 Rules of Datum Feature Simulator Management
- 3.4 Rules of Simultaneous Requirements
- 3.5 Rules of Composite Feature Control Frames
- 3.6 Rule of Material Condition Modifier (S)(M)(L) Applicability
- 3.7 Rule of Material Boundary Modifier (S)(M)(L) Applicability
- 3.8 Rule of Feature Control Frame Stacking (Proposed)

3.1 The Envelope Rule

In the absence of any Material Condition modifier, or in the presence of the modifiers (S) and (M), all Size tools ("Diameter", "Spherical Diameter" and "Thickness") impose envelopes of perfect form at Maximum Material Condition. In the presence of the modifier (L), all Size tools impose envelopes of perfect form at Least Material Condition. (Y14.5 2009 §2.7.1 p.28 + §7.3.5 p.114)

Invocation: The Envelope Rule is invoked globally by default in the Y14.5 2009 Standard.

Explicit Revocation: The Envelope Rule can be revoked explicitly 1) using the Independency modifier (I) (Y14.5 2009 §2.7.3 p.28), and 2) by referencing a "stock material" specification (Y14.5 2009 §2.7.2 p.28).

Automatic Revocation (Y14.5 2009 §5.4.1.2 p.91): The Envelope Rule is automatically revoked when the Diameter tool is accompanied by a Median Line Straightness control, or the Width tool is accompanied by a Median Plane Flatness control, in which case the additional tool takes on the responsibility for controlling global form.

Note 1: This extremely important rule, which applies by default, 1) guarantees assembly of unconstrained mating features of size, 2) enables size tools to impose identical tolerances on form, 3) enables the Position tool to apply to the axes and mid-planes of cylindrical and slab/slot-like features, and 4) enables functional use of the Material Condition modifiers (M) and (L). The failure of the ISO 8015 Standard (one of the ISO set of GD&T Standards) to impose the Envelope Rule by default, disables all four of the gifts delivered by the Y14.5 Standard.

Note 2: The official Y14.5 2009 name of this rule is “Rule #1”. However, since this name fails to identify the rule, and there are no additional numbered rules #2, #3, etc., it is highly recommended that the rule be referred to as “The Envelope Rule”.

3.2 Rules of Natural Datum Reference Frame Establishment

3.2.1 The Rule of Datum Feature Precedence (Y14.5M 2009 §4.10 p.58): Datum Features shall be used in the order in which they appear in the defining Feature Control Frame, reading from left to right.

3.2.2 The Rule of Degrees of Constraint Precedence (*SmartGD&T*): Each Datum Feature shall first attempt to constrain pitch and yaw, then roll and only then, any remaining degrees of translational freedom.

3.2.3 The Rule of Non-Override (*SmartGD&T*): No Datum Feature may override degrees of freedom partially or wholly constrained by higher precedence Datum Features.

3.2.4 The Can-May-Must Rule (*SmartGD&T*): If a Datum Feature can (is able to) and may (is permitted to) constrain a degree of freedom, it must.

Note: These rules, only partially present in the Y14.5 2009 Standard, represent the natural processes which occur when mating parts are assembled and must be followed in CAD and Coordinate Metrology processes. For more insights see the Datum Reference Frame Establishment Process illustration at the end of this document.

3.3 Rules of Datum Feature Simulator Management

(Y14.5 2009 §4.5.2 p. 53 + §4.11.3 p.59 + *SmartGD&T*):

3.3.1 DFS Form Control!: All Datum Feature Simulators shall have “perfect” form.

3.3.2 DFS Orientation Control!: All Datum Feature Simulators shall be “perfectly” oriented relative to one another by the Basic angles of their associated Datum Features.

3.3.3 DFS Size (Boundary) Control!: The Material Boundary modifier

(S) Requires the DFS to expand or contract toward the in-space surface of the associated Datum Feature and impose DRF stability.

(M) Requires the DFS to be fixed at its Virtual Maximum Material (M) boundary and permit residual in-space DRF mobility.

(L) Requires the DFS to be fixed at its Virtual Least Material (L) Boundary and permit residual in-material DRF mobility.

Special Case: When applied to a non-straddling, location constrained, planar Datum Feature which

serves to constrain only rotational degrees of freedom, the modifiers (M) and (L) impose “stability” by requiring the Datum Feature to remain in contact with its simulator under force.

Reminder: Material Boundary modifiers apply to all Datum Feature types except non-location constrained, planar Datum Features, which fall under the Rule of Rocking & Rolling Planar Datum Feature Simulation.

3.3.4 DFS Location Control:

Non-Planar Datum Feature Simulators

1) In the absence of a) a note to the contrary or b) the Translation modifier ►, or c) the moveable Datum Target symbol, all non-planar DFSs shall be fixed at the Basic locations of their defining Datum Features.

2) In the presence of the Translation modifier ► (see the “Rule of Translation Modifier Applicability”) or the moveable Datum Target symbol, all applicable DFSs shall be free to translate toward or away from the origin or primary axis of the interim DRF under the remaining influence of the specified TZM (Material Boundary) modifier.

Planar Datum Feature Simulators

1) The behavior of DFSs associated with non-location constrained planar Datum Features is determined by the Rule of Rocking & Rolling Planar Datum Feature Simulation.

2) The behavior of location constrained planar DFSs is determined by the “Rules of DFS Size (Boundary) Control”.

3.3.5 Rule of Rocking & Rolling, Planar Datum Feature Simulation

(Y14.5 2009 §4.11.2 p.59 + Y14.5.1M 1994 §4.3.2 pp.13-15):

Non-location constrained, potentially unstable (slightly convex) planar Datum Features shall be simulated “rocking” when serving to orient the primary DRF axis, or “rolling” when serving to align remaining DRF axes. In particular, the resulting Datum Reference Frames shall be free to pitch and yaw, or roll, to whatever extent functionally possible, in order to assist in meeting the geometric requirements of features referenced to them.

Note 1: The permissible mobility limits of the rocking and rolling DFS tangent planes, referred to as “candidate datums”, are defined in the Y14.5.1 M 1994 Standard §4.3.2 pp.13-15.

Note 2: Should stable simulation be preferred as more representative of the assembly process, this can be imposed with a constraint note, and refined for coordinate metrology using two alternative methods:

1) by requiring the Datum to be the in-space surface of the minimum slab-like zone which just contains all the points on the Datum Feature (the Chebyshev best fit algorithm), or much more functionally 2) by requiring the Datum to be a force constrained tangent plane using a normal force vector passing through the centroid of the Datum Feature by default, or passing through a note designated surface point.

Note 3: This rule could be “encoded” by enabling the use of the TZM (Tolerance Zone Mobility) modifiers (S), (M) and (L), on non-location constrained planar Datum Features.

Warning: All tolerance zones referenced to Rocking & Rolling (mobile) Datum Reference Frames are beholden to the Rules of Simultaneous Requirements.

3.4 Rules of Simultaneous Requirements

(Y14.5 2009 §4.19 p.76 + Fig. 4-39 p.79 + Fig. 7-46 p.141 + §7.5.4 p.146 + Figs. 8-14, 8-15, 8-16 p.166)

Although somewhat confusing based on the above entries, these rules can be clearly set forth as follows:

- a) Collections of tolerance zones specified in a **single** Feature Control Frame by a grouping tool and a Position or Surface Profile tool, with or without Datum Feature references, form a “**local simultaneous set**” by default.
- b) Collections of tolerance zones specified in **multiple** Feature Control Frames by the Position or Surface Profile tools, which reference the same primary Datum Feature, or the same primary and secondary Datum Features, or the same primary, secondary and tertiary Datum Features with the same Material Boundary modifiers, but which fail to fully constrain all degrees of freedom, form an “**extended simultaneous set**” with respect to their shared Datum Features by default. If need be, selected subgroups can be explicitly excluded from the set using the SEP REQT modifier, or separately grouped using the SIM REQT modifier.
- c) Collections of tolerance zones specified in **multiple** Feature Control Frames by the Position or Surface Profile tools, which reference **no** Datum Features, form “**separate sets**” by default, but can be made **simultaneous** using the SIM REQT modifier.
- d) All tolerance zones specified in the second and all lower tiers of **Composite Feature Control Frames** form “**local simultaneous groups**” by default, unless accompanied by SIM REQT modifiers which turn them and their associated SIM REQT tolerance zone sets into an “**extended simultaneous group**”.

Grouping and Ungrouping Tools:

“Local” tolerance zone groups are created by the feature grouping tools: nX, multiple leaders, <CF>, All Around, Between, and ALL OVER. Local tolerance zone groups can be ungrouped using the INDIVIDUALLY modifier (Y14.5 2009 Fig. 8-23 + §8.6.2 p.175).

“Global” tolerance zone groups consist of extended groups of local tolerance zones and are created by default by the Rules of Simultaneous Requirements or on special demand, by the Feature Control Frame grouping tool: SIM REQT. Global tolerance zone groups can be ungrouped using the SEP REQT modifier.

Currently Applicable Geometry Control Tools: Position and Surface Profile.

Notes: It is recommended that a future release of the Y14.5 Standard

- 1. enable the following additional Geometry Control Tools to also form simultaneous sets: Angularity, Parallelism, Perpendicularity, Circular Runout and Total Runout, to fully represent reality,
- 2. add the suffix “#n” to the SIM REQT modifier to clearly state which specially selected SIM REQT groups are intended to join forces, and
- 3. make the second and all lower tiers of Composite Feature Control Frames simultaneous requirements by default, which they are naturally.

3.5 Rules of Composite Feature Control Frames

(Y14.5M 2009 §7.5.1.8 pp 135)

- a. In general, Datum Features are required to constrain both rotational and translational degrees of freedom, however, those listed in the second and all lower tiers of a Composite FCF must act together to constrain only rotational degrees of freedom.
- b. In the absence of SIM REQT#n modifiers, the second and all lower tiers of Composite FCFs represent SEP REQTs by default. (Note: This rule does not make functional sense and should be eliminated. See also: the Rules of Simultaneous Requirements).

3.6 Rule of Material Condition (Tolerance Zone Size) Modifier (S)(M)(L) Applicability

(No such rule is found in Y14.5M 2009)

The Material Condition modifiers (S), (M) and (L) apply only when the controlled component of the Considered Feature is a symmetry component, namely an axis, a median line, a mid-plane, a median plane or a mid-point.

3.7 Rule of Material Boundary (Tolerance Zone Mobility) Modifier (S)(M)(L) **Applicability** (No such rule is found in Y14.5M 2009)

The Material Boundary modifiers (S), (M) and (L) apply to every Datum Feature type except non-location constrained, planar Datum Features.

3.8 Rules of Feature Control Frame Stacking (Proposed) (No such rule is found in Y14.5M 2009)

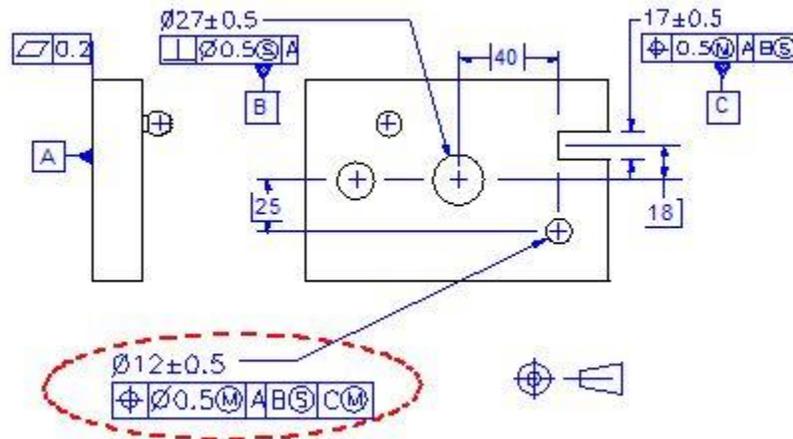
- 1) All controls applied to a feature or to a pattern of features shall appear in a single stack.
- 2) All FCF stacks shall first impose size constraints (if applicable) using toleranced nominal or Basic dimensions, then location constraints (if applicable), then orientation constraints (if applicable), followed, in the case of the Surface Profile tool, by possibly refined size and form constraints, and then form constraints. All Datum Features and Material Boundary modifiers specified in successive tiers of FCF stacks which reference the same Geometry Control tool shall be identical to those in the previous tier, minus deletions from the right, and all tolerance values shall decrease from top to bottom.
- 3) Special Case: If an orientation and/or location constraining FCF referencing different Datum Features is added to a stack, it shall be added at the bottom of said stack.

4. Processes

In order to produce valid GD&T efficiently we need to discover, master and apply processes. In this section we address the following processes:

- 4.1 "Datum Feature Selection"
- 4.2 "Datum Feature Sequencing"
- 4.3 "Geometry Control Tool Selection"
- 4.4 "Material Condition Modifier Selection"
- 4.5 "Material Boundary Modifier Selection"
- 4.6 "Feature Control Frame Stuffing"
- 4.7 "Virtual Maximum Material Boundary Determination"
- 4.8 "Feature Control Frame Decoding"
- 4.9 "Datum Reference Frame Establishment",

always referring to the following drawing:



4.1 The Datum Feature Selection Process

In most cases, the most functional Datum Features are those which engage mating features on the largest associated mating part during the assembly process to constrain their mutual degrees of freedom. Because the “fundamental” Datum Features of a part serve to define the coordinate system relative to which most of its remaining features will be oriented and located and which needs to be functionally “capable” of doing so, if the largest mating part is less than half the size of the part under consideration, features which are more “capable”, rather than simply mating features, may need to be selected. In the case illustrated above, the actual mating features are the bottom planar surface, the central bore and the slot, which are very “capable” and have been identified as Datum Features.

4.2 The Datum Feature Sequencing Process

Given a selected group of Datum Features, the order in which they should be sequenced is determined by their degrees of freedom constraining capabilities. The primary Datum Feature shall be the one most capable of constraining the most important degrees of freedom, namely “pitch” and “yaw”, in this case the planar surface identified as A. The secondary Datum Feature shall be the one most capable of constraining the most important remaining degrees of freedom, in this case the two remaining degrees of translational freedom, namely the central bore identified as B. The tertiary Datum Feature must and can constrain the remaining degree of freedom, roll, namely the slot identified as C.

4.3 The Geometry Control Tool Selection Process

In order to select the proper Geometry Control tool or tools, we must determine “what can go wrong” with each feature of a part. Datum Feature A: The only problem planar surface A can suffer is form, in particular flatness, which is best controlled with the Flatness tool. Datum Feature B: The only problems bore B can suffer are size and form, and orientation relative to A. The best tool for controlling size and form is the Diameter tool, which does the latter as a result of the Envelope Rule. The best tool for controlling orientation in this case is Perpendicularity applied to the axis. Datum Feature C: The problems C can suffer are size, form, orientation and location. The best tool for controlling size and form is the Width tool, and for controlling orientation and location is the Position tool, which does both. The lower right hand bore: The bore can suffer all four problems and all four are very effectively dealt with using the Diameter and the Position tools.

4.4 The Material Condition (TZS) Modifier Selection Process

No material condition modifiers apply to controls on Datum Feature A, but do apply to both B and C, because both the Perpendicularity and the Position tools deal with their symmetry components. Given these facts, the functionally correct modifiers for B and C need to be selected, namely (S), (M) or (L)? Since Datum Feature

B serves a “locating” function, the proper Material Condition modifier is (S). If it can be proven that C serves a not highly critical clocking function, why not give the machine shop a gift and select (M) as shown in the drawing?

4.5 The Material Boundary (TZM) Modifier Selection Process

No Material Boundary (Tolerance Zone Mobility) modifiers apply to Datum Feature A, because it is a non-location constrained planar Datum Feature (even though the hope is that they will be made to do so someday). However, Material Boundary (TZM) modifiers do apply to Datum Features B and C. In order to deal properly with the locating (centering) responsibility of B we will use the modifier (S) to encode “stability”, and in order to deal realistically with the clocking responsibility of C, which will surely experience residual play with its mating feature during assembly, we will use the modifier (M) to encode permissible “mobility”.

4.6. The Feature Control Frame Stuffing Process

Feature Control Frame stuffing is the process of inserting Geometry Control Tools, Tolerance Zone Shape modifiers, Tolerance values, Material Condition and other modifiers associated with the tolerance zone, Datum Feature labels and ultimately Material Boundary modifiers in a logical, function sensitive way. The results of this process are seen in the four Feature Control Frames found in the drawing above.

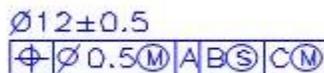
4.7 The Virtual Maximum Material Boundary Determination Process

As will become evident when we “decode” the encircled Feature Control Frame in the illustration above, Datum Feature C must be simulated at its Virtual Maximum Material Boundary. The VMMB of Datum Feature C is the size of the largest orientation and location constrained slab which can be guaranteed to fit inside it under the worst conditions, namely must be smaller than its smallest width of 16.5mm, and must shrink further to accommodate its most tilted condition of 0.5mm, and thus have a width of 16mm.

4.8 The Feature Control Frame Decoding Process

If GD&T is to have any value, it must not be open to “interpretation”, namely may only mean one thing, requiring users to learn how to “decode” it. Focusing on the encircled Feature Control Frame in the illustration above and shown again below, let us first “read” it and then “decode” it.

The “reading”: “Position within a diameter of 0.5mm at MMC, relative to A, relative to B regardless of its material boundary, and relative to C at its maximum material boundary.”



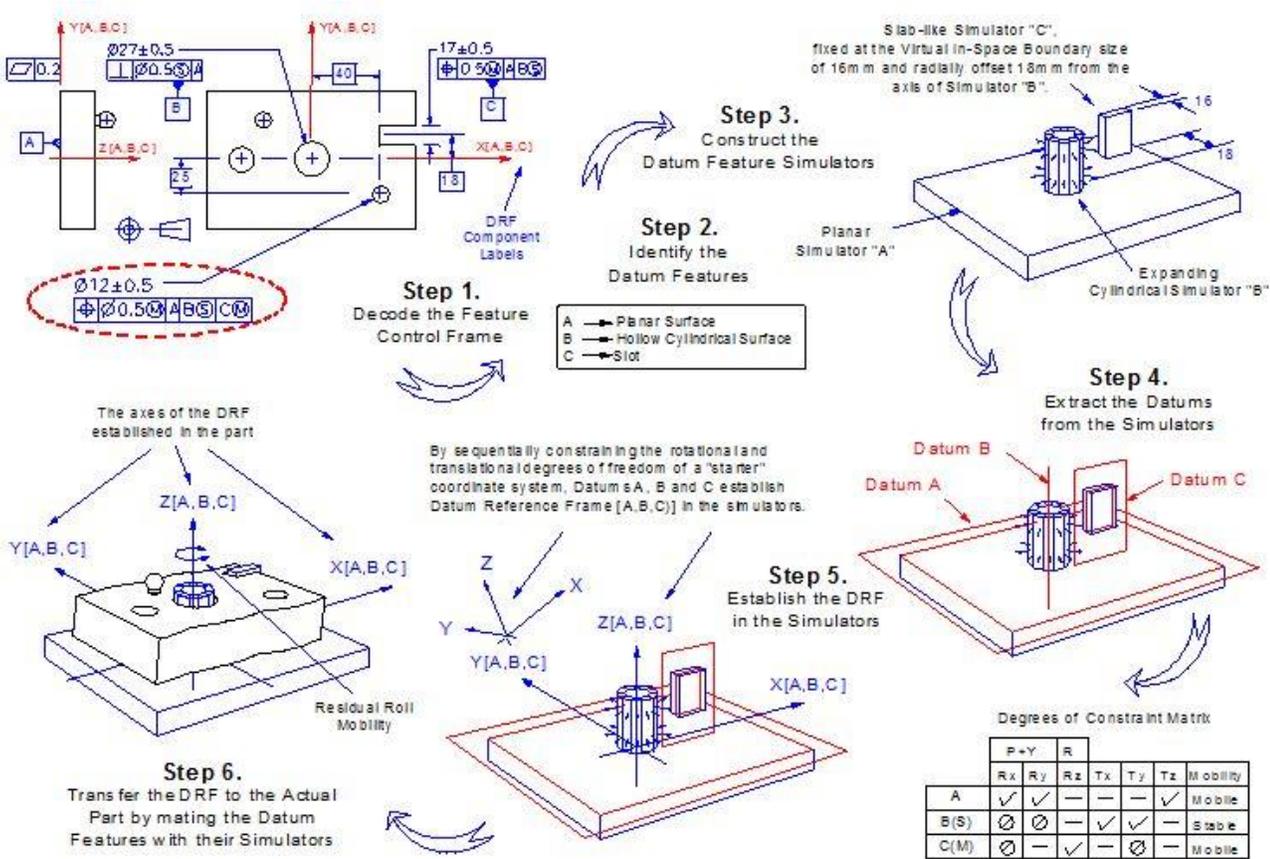
The “decoding”: “Position requires the bounded axis of the bore to lie within a cylindrical tolerance zone of diameter 0.5mm at MMC, expanding by as much as 1mm as the bore departs from MMC toward LMC, which is oriented and located by Basic dimensions relative to a Datum Reference Frame established using Datum Feature A simulated “rocking”, Datum Feature B simulated “stably” regardless of its Material Boundary, and Datum Feature C simulated “mobly” at its Virtual Maximum Material Boundary.”

Note: The term “rocking” is defined in Y14.5 2009 §4.11.2 (p.59). The terms “stably” and “mobly” are not found in the Standard but serve to make very clear the impact of the Material Boundary modifiers (S) versus (M).

4.9 The Datum Reference Frame Establishment Process

The Datum Reference Frame Establishment Process happens in the six steps shown in the illustration below, where the specified Datum Features A, B and C can be seen in step 1, and the resulting Datum Feature Simulators “A”, “B” and “C” can be seen in step 3, with “B” expanding to achieve stability relative to

Datum Feature B, and with “C” fixed in size to permit residual roll relative to Datum Feature C. In step 4, one can see Datums A, B and C extracted from their Datum Feature Simulators, and in step 5, how Datums A, B and C serve to constrain the “starter” coordinate system and turn it into the Datum Reference Frame we’ve been looking for. In step 6 we see how “marrying” the Datum Features to their Simulators enables us to transfer the Datum Reference frame to the actual part, where we hope the bounded axis of the bore can be made to fall inside the Position tolerance zone as it “rolls” back and forth due to the residual mobility of the Datum Reference Frame.



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5. Best Practices

Just a quick list:

5.1 Controlling the Size of Cylindrical and Spherical Features

Use the Diameter and Spherical Diameter tools if their surfaces subtend angles greater than 180° and the Surface Profile tool in all other instances.

5.2 Explicit Datum Reference Frame Axis Labeling

Use the DRF axis labels X[A,B,C], Y[A,B,C] and Z[A,B,C] in every CAD model and drawing to specify the preferred basis for all coordinate metrology generated reports to enable efficient comparison of inspection reports generated in-house and by external suppliers.

5.3 Ordinate Dimensioning

Always use ordinate dimensions to enable efficient coordinate metrology reporting.

5.4 Breaking the Symmetry of Symmetric Parts

The symmetry of symmetric parts must be broken when GD&T controls are applied asymmetrically, and may be wisely broken to enable assessment and refinement of potentially asymmetric manufacturing processes.

5.5 Constraint Requirements for Non-Rigid Parts - Sheet Metal, Rubber & Plastic

Specifications for all non-rigid parts must include precisely defined constrained condition notes in order to minimize manufacturing costs and to guarantee functional metrology and effective manufacturing feedback.

5.6 Threaded Feature Management

All orientation and location controls imposed on the axes of threaded features must use the Material Condition modifier (S) to encode their automatically self-centering behavior. All orientation and location controls imposed on the axes of threaded bores shall use the Projection modifier (P) to encode the mating impact and guarantee assembly.

Conclusions

Reader feedback on these efforts would be much appreciated by Quality Magazine and if substantial, might be presented in a follow-up article, to be made available online. Thank you!