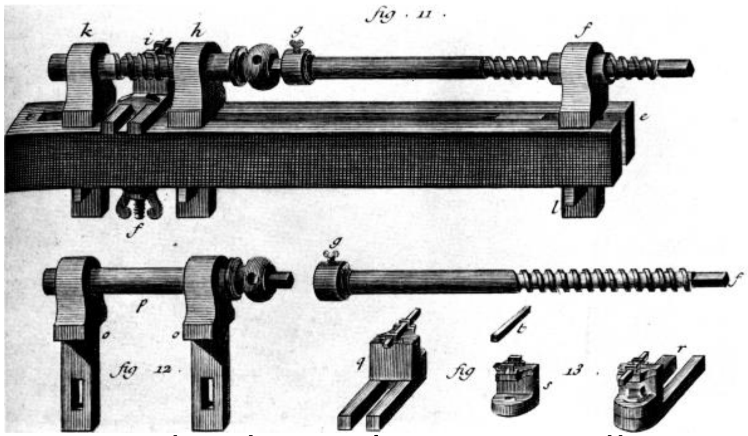
Tolerancing and Dimensioning

Doing things right the first time adds nothing to the cost of your product of service. Doing things wrong is what costs money. – Philip B. Crosby

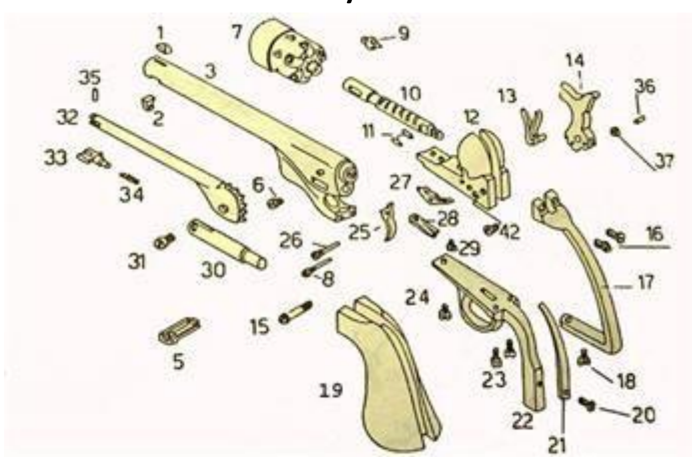
Why bother?

- Interchangeable Parts

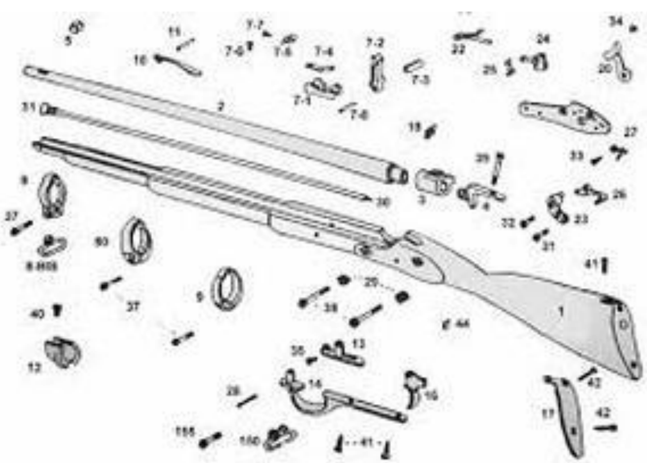


Eli Whitney's Cotton Mill

Early 1900's assembly line



Colt Peace Maker



Springfield 1856

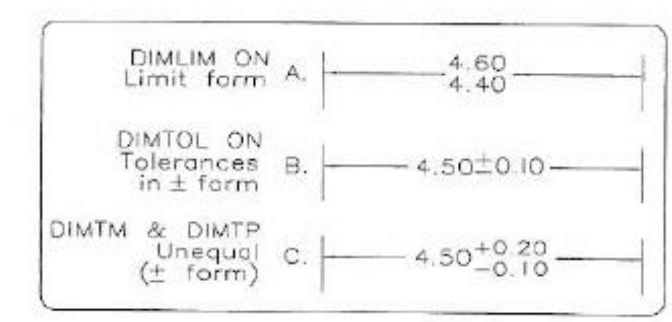
Tolerancing and Dimensioning Goals

- Tolerancing
  - Allow individual parts to assemble and properly operate together as a single system

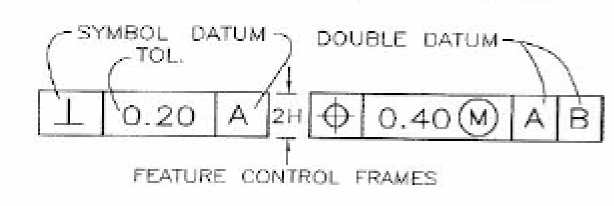
- Dimensioning
  - Exercise in Precise Communication
    - Typically a graphical representation of the part or assembly that provides a clear depiction and description of:
      - Geometry
        - » Shape
      - Size
        - » Dimensions
        - » Tolerances
        - » Description (material, finish, etc.)
      - Intent is clear
        - » Size and location of all features is mutual understood
          - Standards
            - ANSI
            - ISO

Tolerancing

- Motivation: Cannot make a part *exactly* the right size
  - A certain amount of variation on each dimension must be tolerated
- Example: Size limits
  - Unilateral/bilateral
  - Limit



  - Geometric



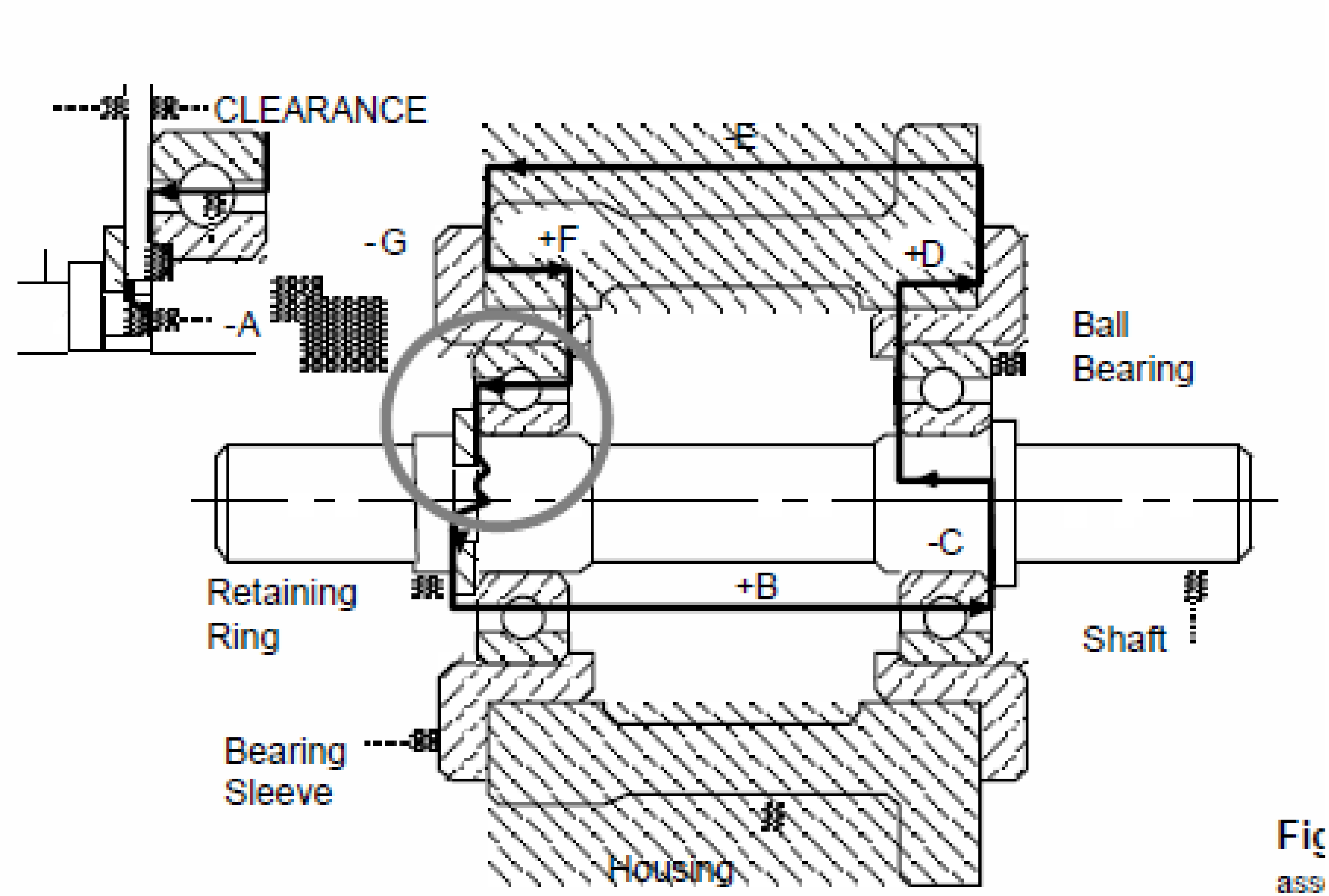
Considerations

but avoid “over-the-wall” thinking

- Engineering Driven
  - Any tolerance necessary to ensure the perceived functional requirements of a product – “over-the-wall”
- Process Driven
  - Based entirely on the capability of the manufacturing process – manufacturing dictates design requirements to engineering
- Inspection Driven
  - Expected measurement/gauging technique dictates dimensioning scheme and tolerancing

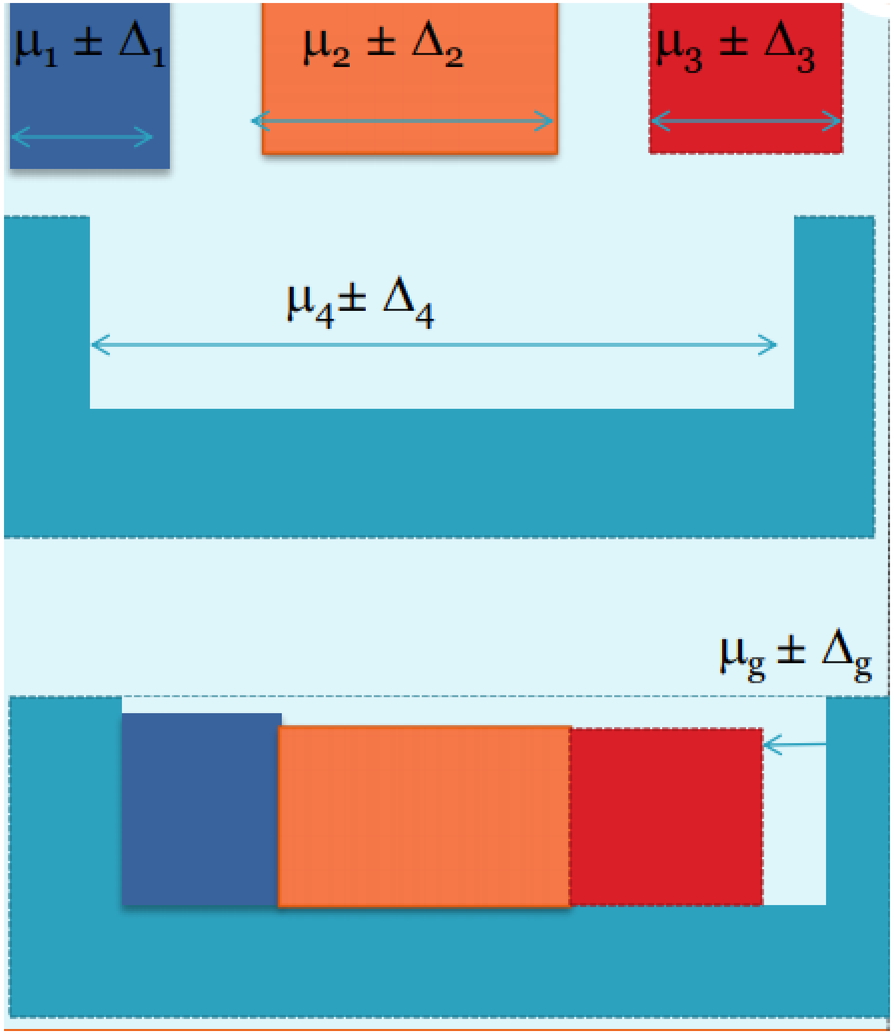
Engineering Driven

Tolerance Stackup process



Tolerance Stack up

- Adding/subtracting tolerances
  - Worst Case
  - Good for:
    - Design verification
    - Catastrophic failure
    - Low number of parts (3-5)
- Statistical
  - Sum variance



Engineering Driven

- Performance Requirements

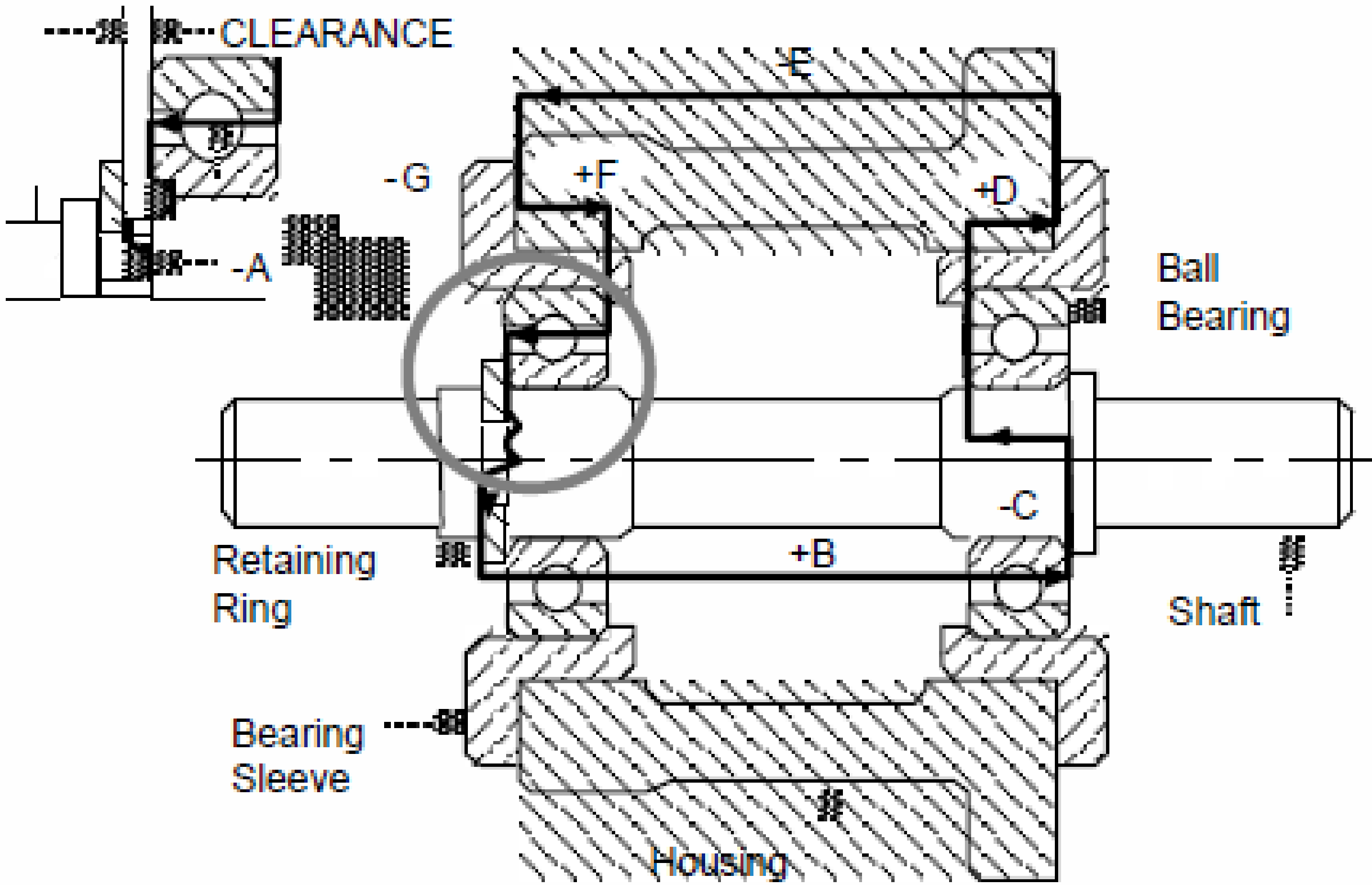
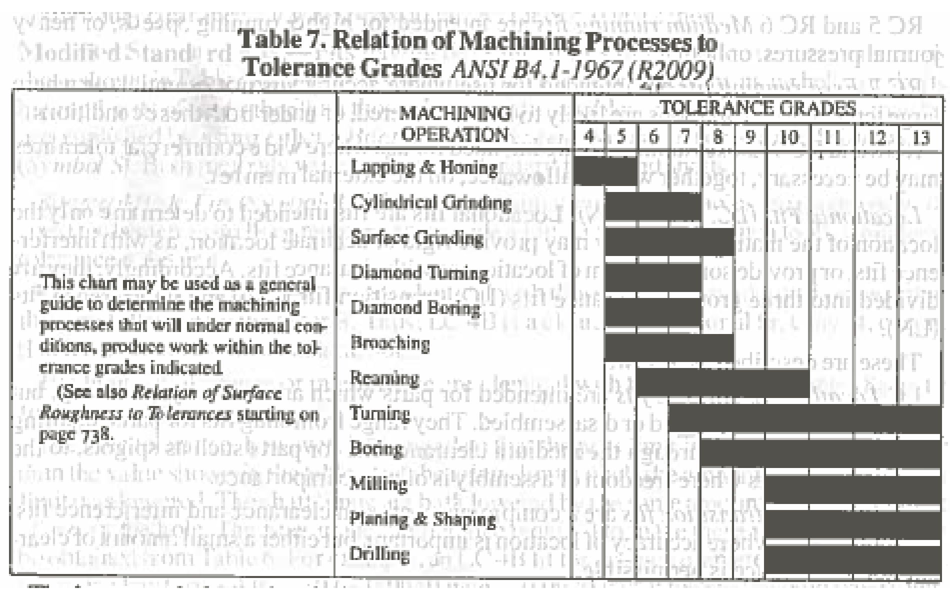


Fig
ass

Process Driven

- Tolerance Grades

	Measuring Tools									Material								
IT Grade	**01**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
							Fits							Large Manufacturing Tolerances				



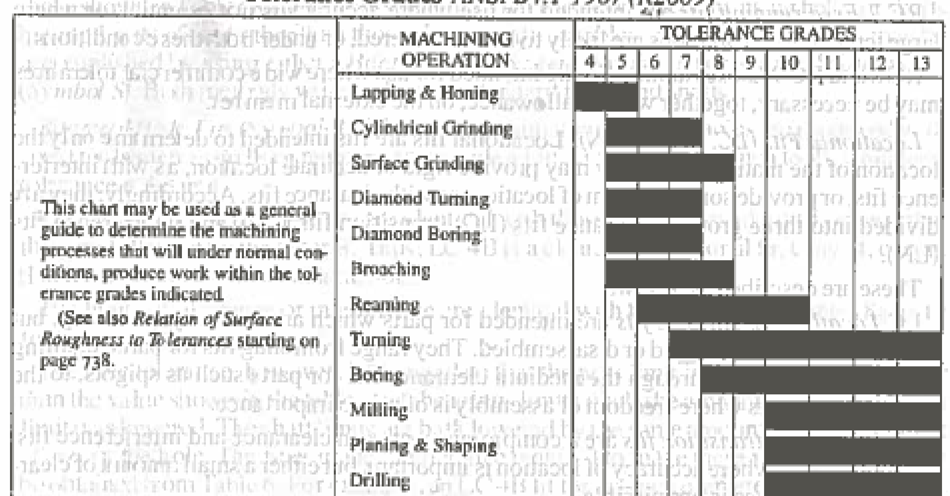
Process Driven

Table 6. ANSI Standard Tolerances *ANSI B4.1-1967 (R2009)*

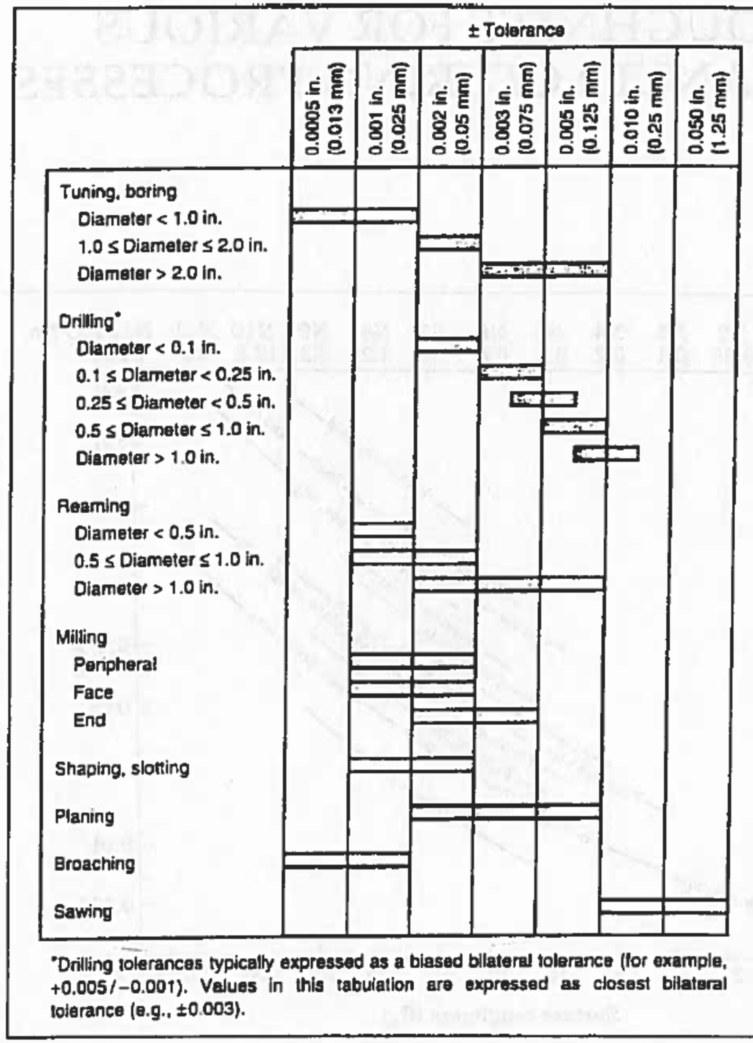
Nominal Size, Inches		Grade									
		4	5	6	7	8	9	10	11	12	13
Over	To	Tolerances in thousandths of an inch[a]									
0	0.12	0.12	0.15	0.25	0.4	0.6	1.0	1.6	2.5	4	6
0.12	0.24	0.15	0.20	0.3	0.5	0.7	1.2	1.8	3.0	5	7
0.24	0.40	0.15	0.25	0.4	0.6	0.9	1.4	2.2	3.5	6	9
0.40	0.71	0.2	0.3	0.4	0.7	1.0	1.6	2.8	4.0	7	10
0.71	1.19	0.25	0.4	0.5	0.8	1.2	2.0	3.5	5.0	8	12
1.19	1.97	0.3	0.4	0.6	1.0	1.6	2.5	4.0	6	10	16
1.97	3.15	0.3	0.5	0.7	1.2	1.8	3.0	4.5	7	12	18
3.15	4.73	0.4	0.6	0.9	1.4	2.2	3.5	5	9	14	22
4.73	7.09	0.5	0.7	1.0	1.6	2.5	4.0	6	10	16	25
7.09	9.85	0.6	0.8	1.2	1.8	2.8	4.5	7	12	18	28
9.85	12.41	0.6	0.9	1.2	2.0	3.0	5.0	8	12	20	30
12.41	15.75	0.7	1.0	1.4	2.2	3.5	6	9	14	22	35
15.75	19.69	0.8	1.0	1.6	2.5	4	6	10	16	25	40
19.69	30.09	0.9	1.2	2.0	3	5	8	12	20	30	50
30.09	41.49	1.0	1.6	2.5	4	6	10	16	25		
41.49	56.19	1.2	2.0	3	5	8	12	20	30		
56.19	76.39	1.6	2.5	4	6	10	16	25	40		
76.39	100.9	2.0	3	5	8	12	20	30	50		
100.9	131.9	2.5	4	6	10	16	25	40	60		
131.9	171.9	3	5	8	12	20	30	50	80		
171.9	200	4	6	10	16	25	40	60	100		

[a] All tolerances above heavy line are in accordance with American-British-Canadiar ments.

Table 7. Relation of Machining Processes to Tolerance Grades *ANSI B4.1-1967 (R2009)*

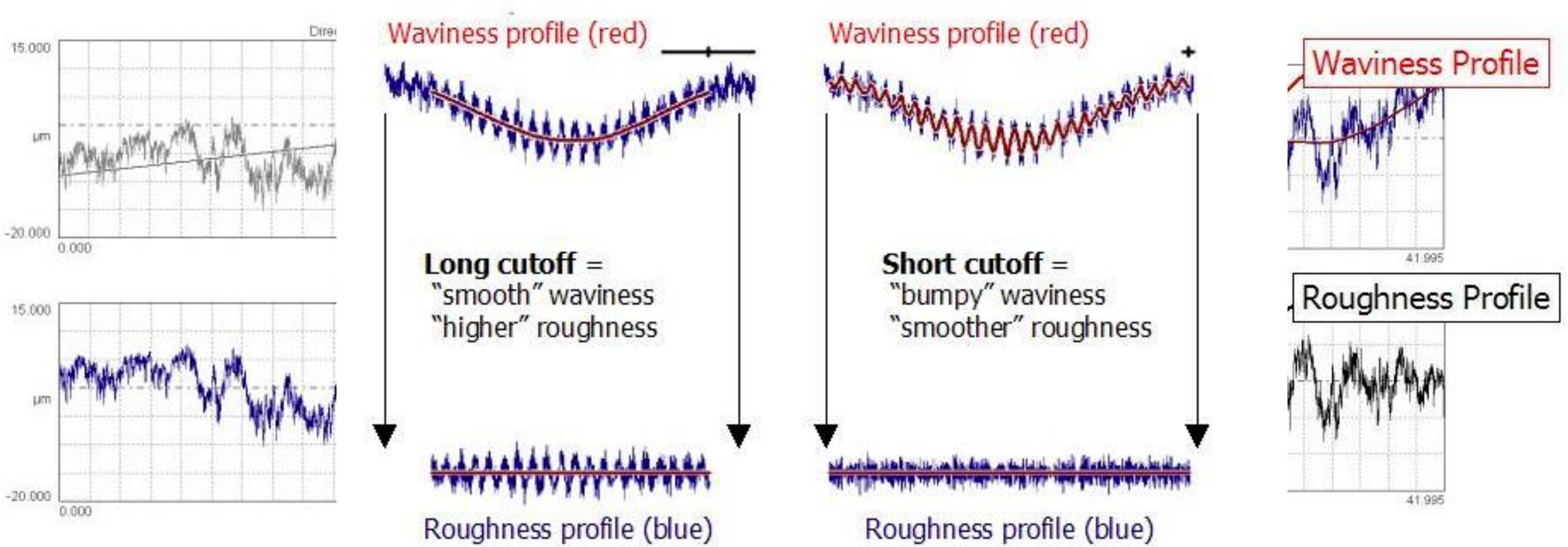


Process Driven

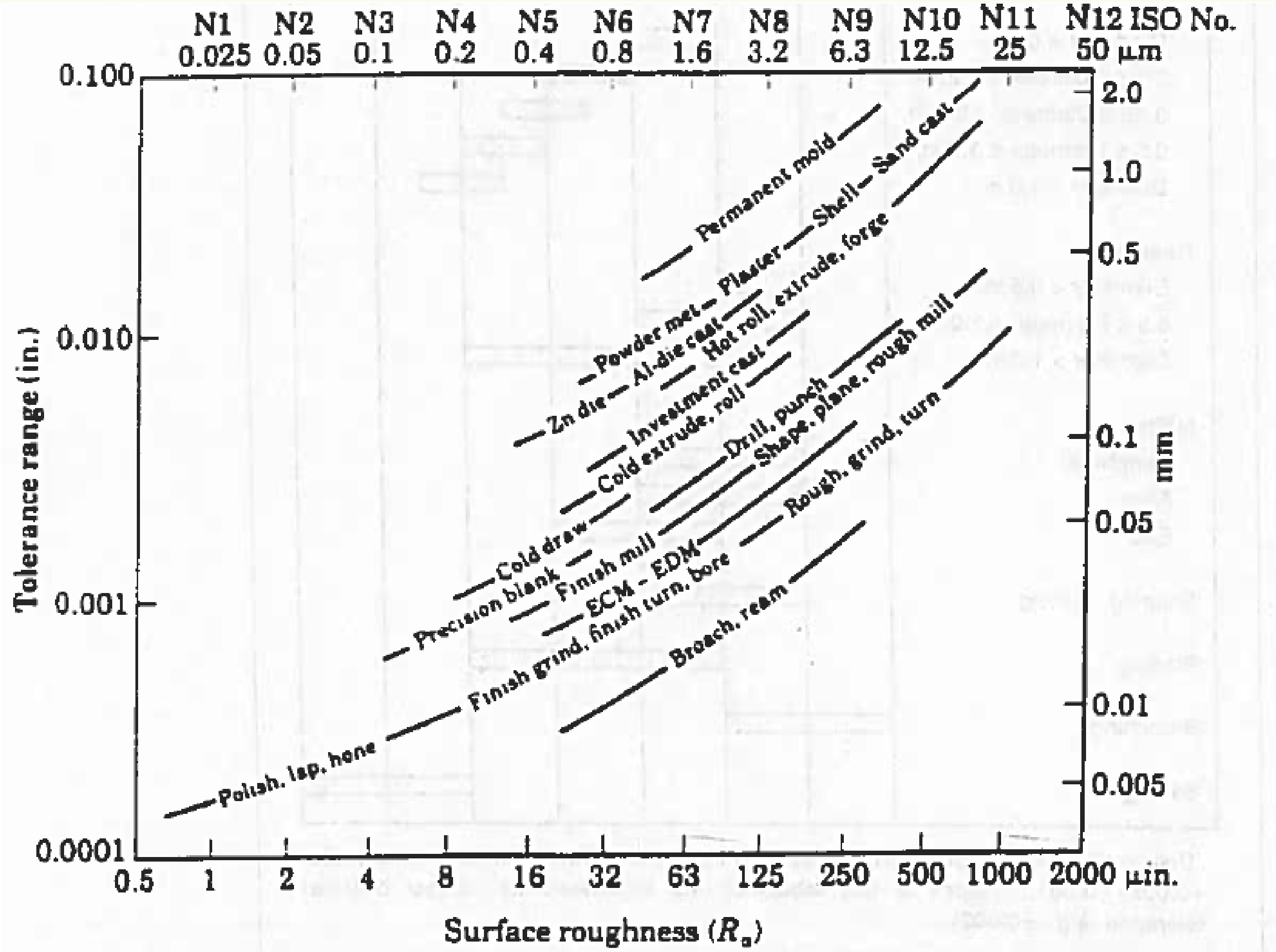


Surface Deviations

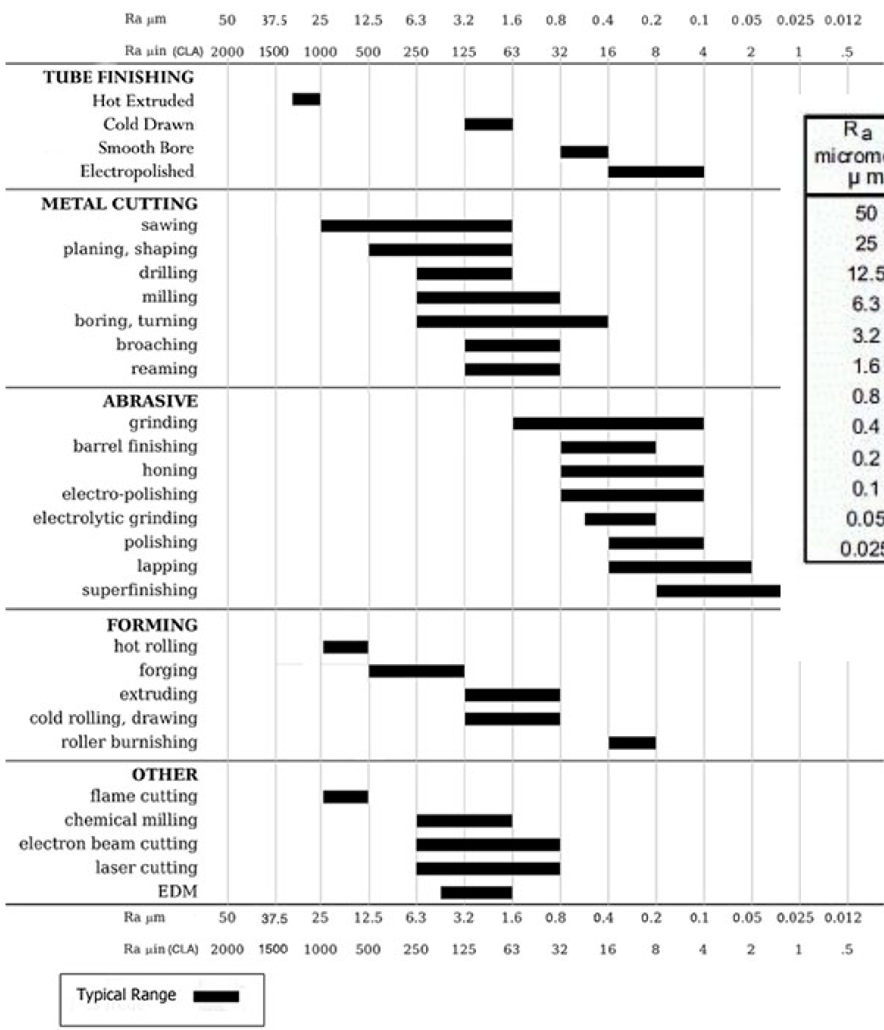
Form, Waviness, Roughness



Process Driven

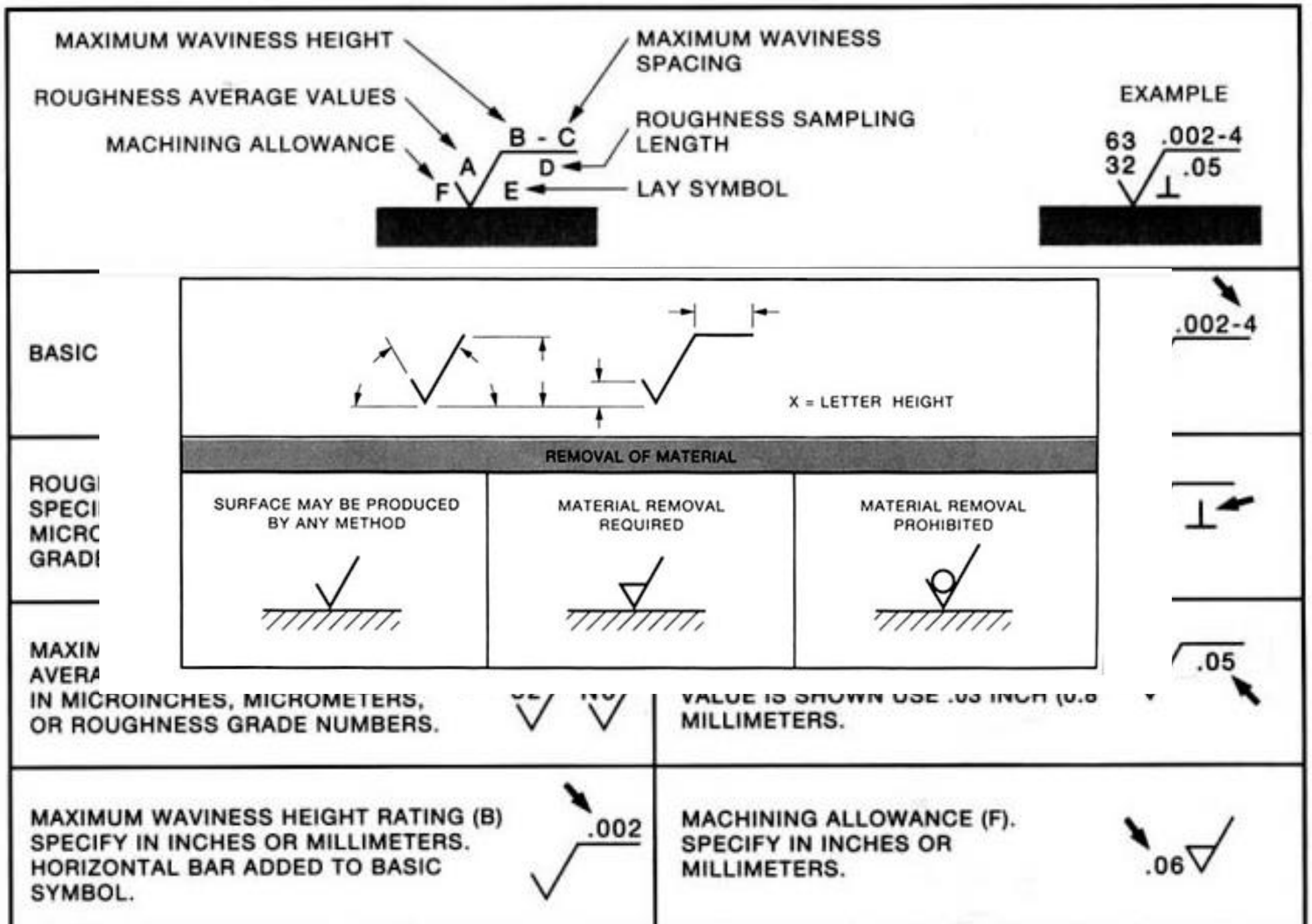


Indicative surface roughness comparisons

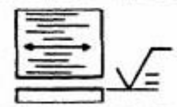
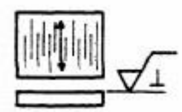
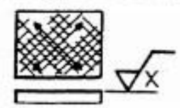
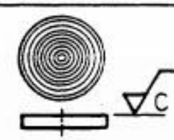
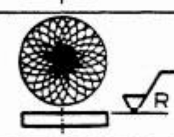
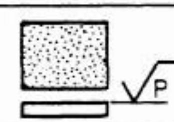


Ra micrometer µm	Ra micro-inch µ in	Roughness Grade Numbers (New)**	Roughness Grade Numbers (Old)***	Rt	▽(Ra)	Old Style	American standard
50	2000	N12					
25	1000	N11	▽				
12.5	500	N10					
6.3	250	N9		32	6.3	32 ▽	250 √
3.2	125	N8	▽▽	16	3.2	▽▽	125 √
1.6	63	N7		8	1.6	8 ▽▽	63 √
0.8	32	N6		4	0.8	▽▽▽	32 √
0.4	16	N5	▽▽▽	2	0.4	2 ▽▽▽	16 √
0.2	8	N4		1	0.2	▽▽▽▽	8 √
0.1	4	N3		0.5	0.1	0.5 ▽▽▽▽	4 √
0.05	2	N2	▽▽▽▽	0.25	0.05	0.25 ▽▽▽▽	2 √
0.025	1	N1					

Roughness Grade Numbers and Ra Measures…



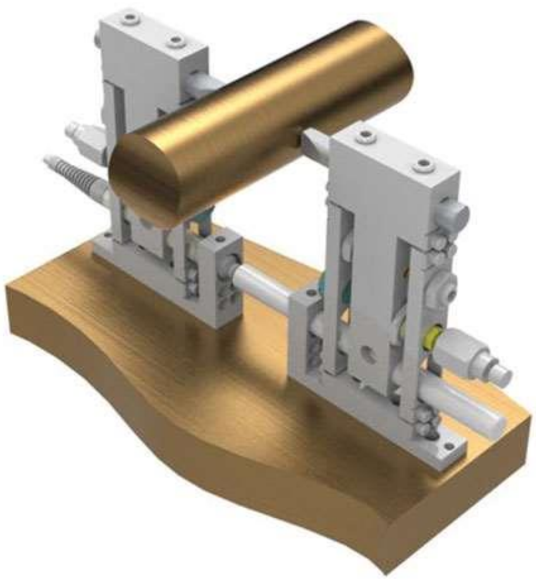
NOTE: WAVINESS IS NOT USED IN ISO STANDARDS.

Lay Symbol	Meaning	Example Showing Direction of Tool Marks
=	Lay approximately parallel to the line representing the surface to which the symbol is applied.	
⊥	Lay approximately perpendicular to the line representing the surface to which the symbol is applied.	
X	Lay angular in both directions to line representing the surface to which the symbol is applied.	
M	Lay multidirectional.	
C	Lay approximately circular relative to the center of the surface to which the symbol is applied.	
R	Lay approximately radial relative to the center of the surface to which the symbol is applied.	
P[3]	Lay particulate, non-directional, or protuberant.	

MICROMETERS RATING	MICROINCHES RATING	APPLICATION
25	1000	Rough, low grade surface resulting from sand casting, torch or saw cutting, chipping, or rough forging. Machine operations are not required because appearance is not objectionable. This surface, rarely specified, is suitable for unmachined clearance areas on rough construction items.
12.5	500	Rough, low grade surface resulting from heavy cuts and coarse feeds in milling, turning, shaping, boring, and rough filing, disc grinding and snagging. It is suitable for clearance areas on machinery, jigs, and fixtures. Sand casting or rough forging produces this surface.
6.3	250	Coarse production surface, for unimportant clearance and cleanup operation, resulting from coarse surface grind, rough file, disc grind, rapid feeds in turning, milling, shaping, drilling, boring, grinding, etc., where tool marks are not objectionable. The natural surfaces of forgings, permanent mold castings, extrusions, and rolled surfaces also produce this roughness. It can be produced economically and is used on parts where stress requirements, appearance, and conditions of operations and design permit.
3.2	125	The roughest surface recommended for parts subject to loads, vibration, and high stress. It is also permitted for bearing surfaces when motion is slow and loads light or infrequent. It is a medium commercial machine finish produced by relatively high speeds and fine feeds taking light cuts with sharp tools. It may be economically produced on lathes, milling machines, shapers, grinders, etc., or on permanent mold castings, die castings, extrusion, and rolled surfaces.
1.6	63	A good machine finish produced under controlled conditions using relatively high speeds and fine feeds to take light cuts with sharp cuttings. It may be specified for close fits and used for all stressed parts, except fast rotating shafts, axles, and parts subject to severe vibration or extreme tension. It is satisfactory for bearing surfaces when motion is slow and loads light or infrequent. It may also be obtained on extrusions, rolled surfaces, die castings and permanent mold casting when rigidly controlled.
0.8	32	A high-grade machine finish requiring close control when produced by lathes, shapers, milling machines, etc., but relatively easy to produced by centerless, cylindrical, or surface grinders. Also, extruding, rolling or die casting may produce a comparable surface when rigidly controlled. This surface may be specified in parts where stress concentration is present. It is used for bearings when motion is not continuous and loads are light. When finer finishes are specified, production costs rise rapidly; therefore, such finishes must be analyzed carefully.
0.4	16	A high quality surface produced by fine cylindrical grinding, emery buffing, coarse honing, or lapping, it is specified where smoothness is of primary importance, such as rapidly rotating shaft bearings, heavily loaded bearing and extreme tension members.
0.2	8	A fine surface produced by honing, lapping, or buffing. It is specified where packings and rings must slide across the direction of the surface grain, maintaining or withstanding pressures, or for interior honed surface of hydraulic cylinders. It may also be required in precision gauges and instrument work, or sensitive value surfaces, or on rapidly rotating shafts and on bearings where lubrication is not dependable.
0.1	4	A costly refined surface produced by honing, lapping and buffing. It is specified only when he design requirements make it mandatory. It is required in instrument work, gauge work, and where packing and rings must slide across the direction of surface grain such as on chrome plated piston rods, etc. where lubrication is not dependable.
0.05 0.025	2 1	Costly refined surfaces produced by only the finest of modern honing, lapping, buffing, and superfinishing equipment. These surfaces may have a satin or highly polished appearance depending on the finishing operation and material. These surfaces are specified only when design requirements make it mandatory. They are specified on fine or sensitive instrument parts or other laboratory items, and certain gauge surfaces, such as precision gauge blocks.

Surface Finish

Inspection Driven



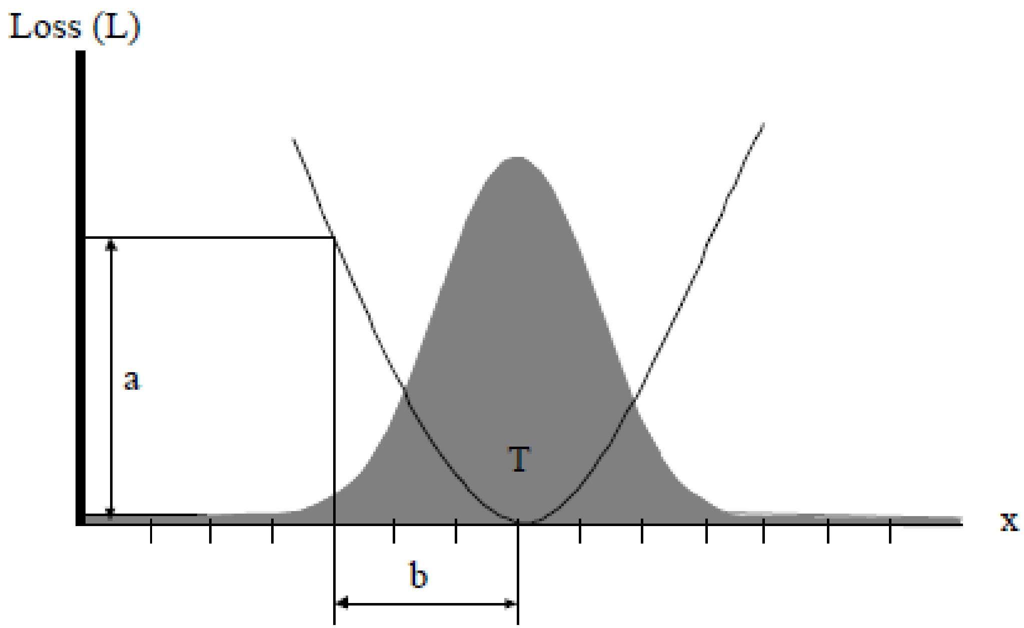
Gauging Techniques

Coordinate Measuring Machine

Taguchi – Customer perception missing

- Monetary losses occur with any deviation from the nominal. – Genichi Taguchi

$$L = \frac{a}{b^2}[(x - T)^2 + \sigma^2]$$



Introducing quality concepts at the design stage is more valuable than through inspection after manufacture

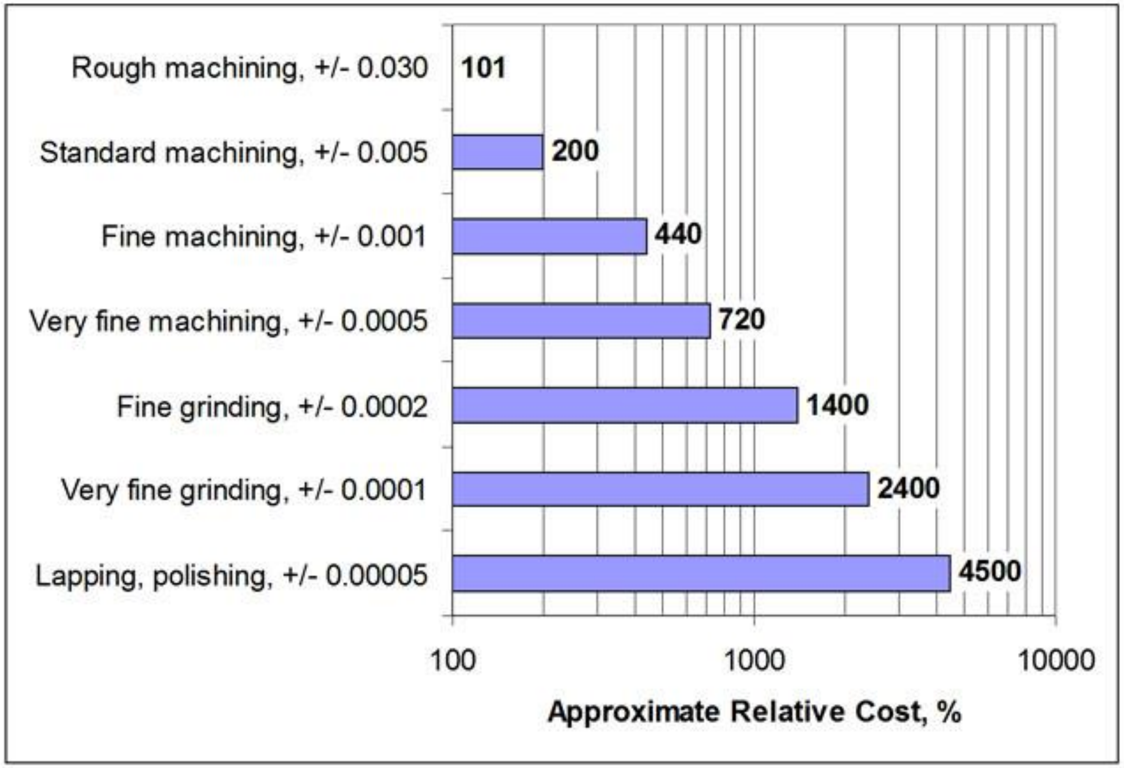
"Standard Rule-of-Thumb" Tolerances

1 decimal place	X.X	± 0.2"
2 decimal places	X.XX	± 0.01"
3 decimal places	X.XXX	± 0.005"
4 decimal places	X.XXXX	± 0.0005"

But be careful with this table, if you are working on a part that measures 3.5" nominal the best tolerance you can expect from milling is 0.005"

- Prescribe the largest tolerances you can afford
  - Budget trade-off
    - Tighter tolerances = more performance (usually)
    - Looser tolerances = less expensive manufacturing (usually)
    - But of course there is Taguchi…
  - Generally, most parts require only a few features to be held to high accuracy

Approximate Relative Cost of Progressively Tighter Dimensional Tolerances



N.E.Woldman, Machinability and Machining of Metals

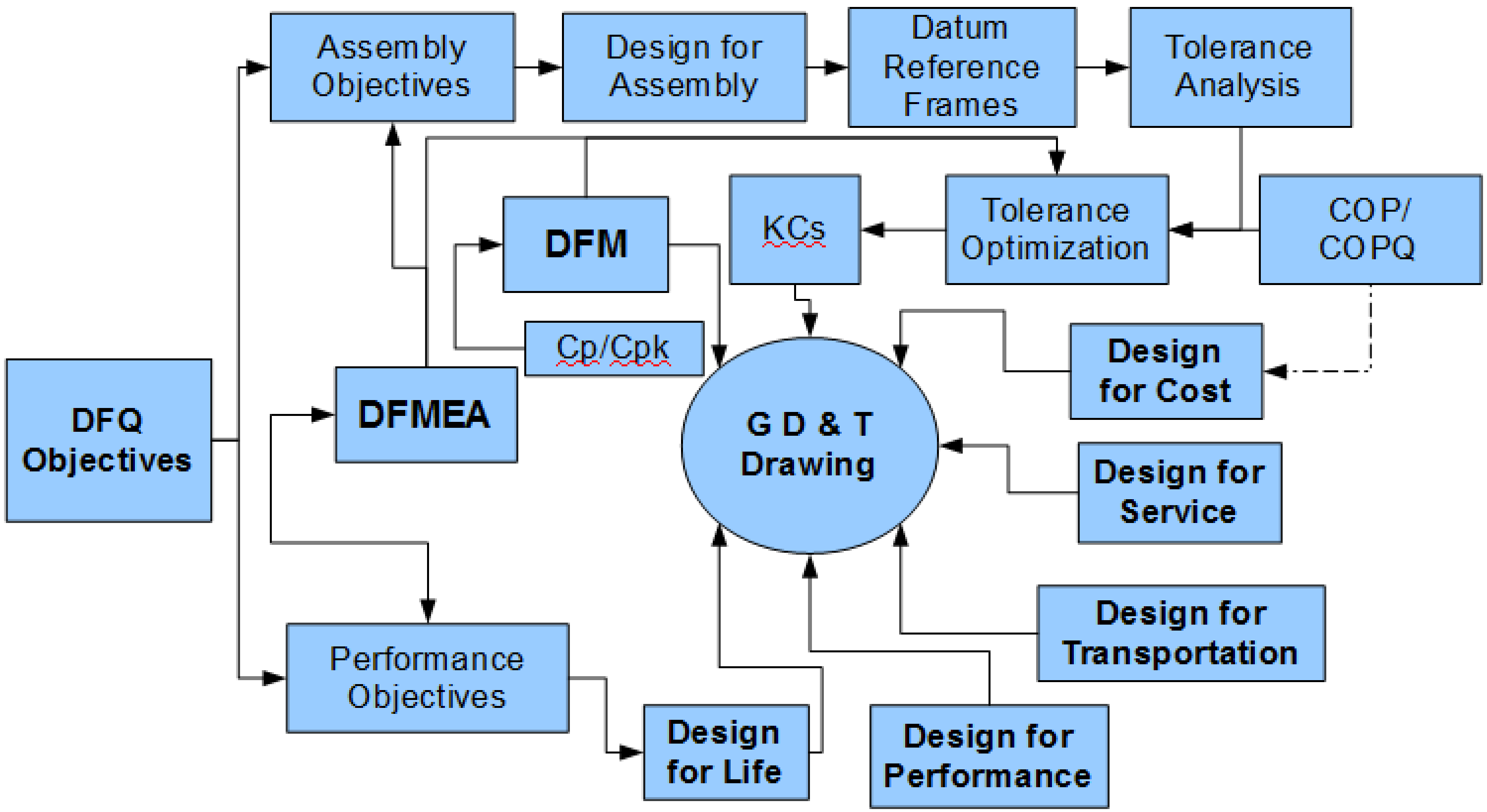
Surface Finish → [9]

Quality

- Meets the need of the customer and thereby provides product satisfaction
- Freedom from deficiencies – absence of defects.

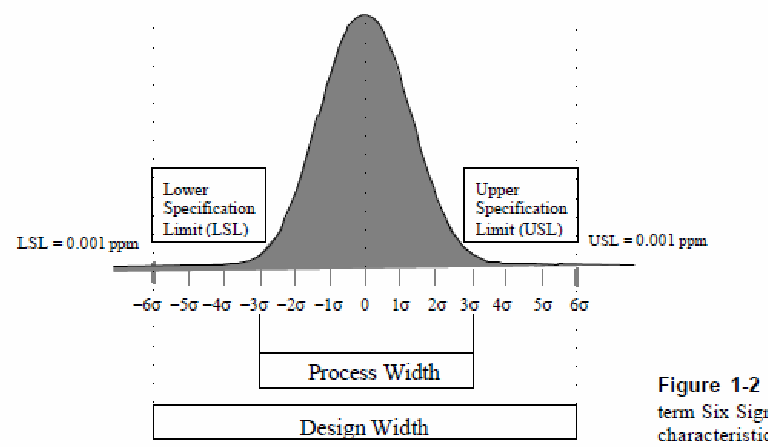
- Standards
  - ISO 9000 series

Design for Quality



Six Sigma

- There is a direct correlation between the number of product defects, wasted operating costs, and the level of customer satisfaction.
- **The Six Sigma measures the capability of the process to perform *defect-free* work.**
  - DFQ Objective: defects per unit
    - Component
    - Piece of Material
    - Line of Code
    - Administrative form
    - Time Frame
    - Distance



Single critical-to-quality (CTQ) characteristic

Cp

- $C_p \equiv$ Capability index or Concurrent Engineering Index: Design / Manufacturing

$$- C_p = \frac{Spec\ Limits}{Process\ Capability} = \frac{USL - LSL}{\pm a\sigma} \Rightarrow \sigma = \frac{T}{aC_p}$$

  - Automotive: $C_p = 1.33$

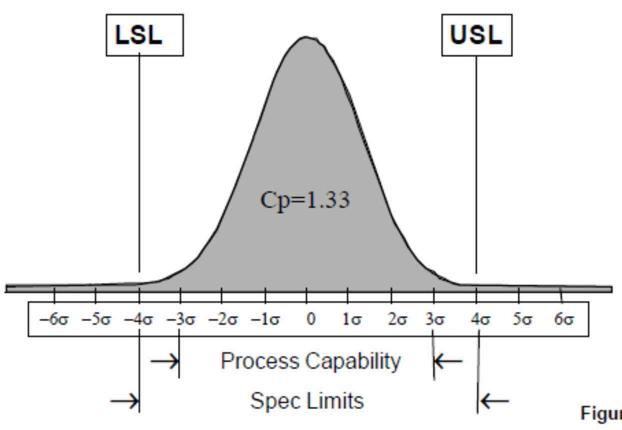


Figure 10-15

Ford motor company 305 BOSS:
Rod and main bores manufacturing tolerances ±.0003".

- Crankshaft
  - Diameter $\approx 2" \pm 0.0003$"
  - $\Rightarrow Process\ Capability = 0.00025$"

Cp

- $C_p \equiv$ Capability index or Concurrent Engineering Index: Design / Manufacturing
  - $C_p = \frac{Spec\ Limits}{Process\ Capability} = \frac{USL - LSL}{\pm a\sigma}$
    - Automotive: $C_p = 1.33$

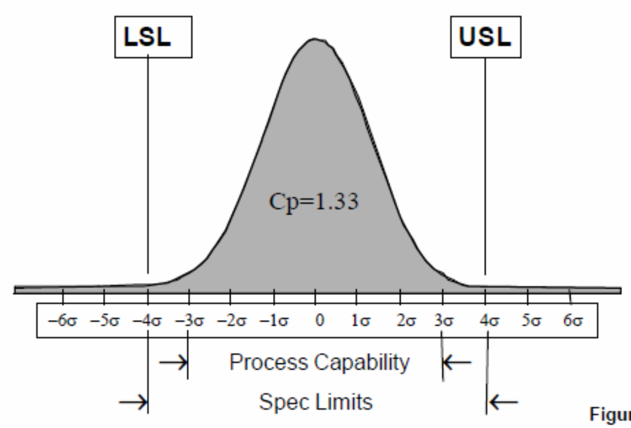


Figure 10-15

Cpk

- $C_{pk} \equiv$ Process capability index adjusted for centering
- $C_{pk} = C_p(1 - k)$
  - $k \equiv$ ratio of the amount the center has moved off target divided by the amount from the center to the nearest specification limit

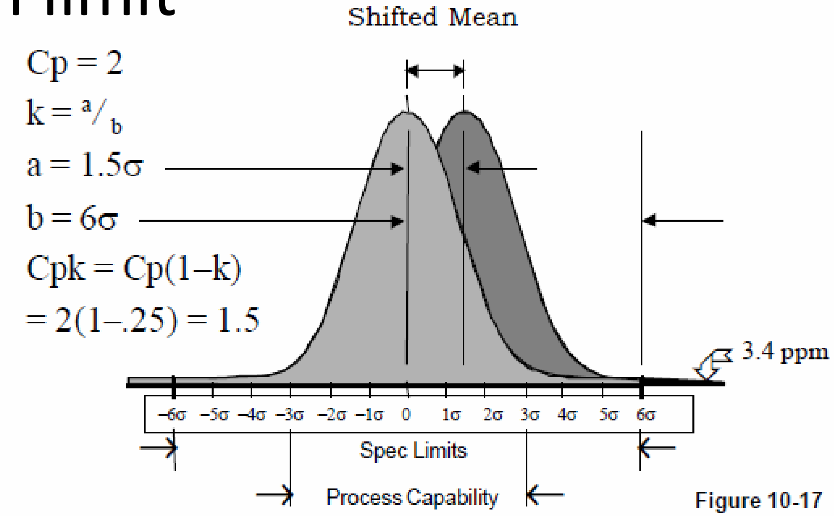


Figure 10-17 Cp and Cpk at Six Sigma

Some Statistical Quality measures

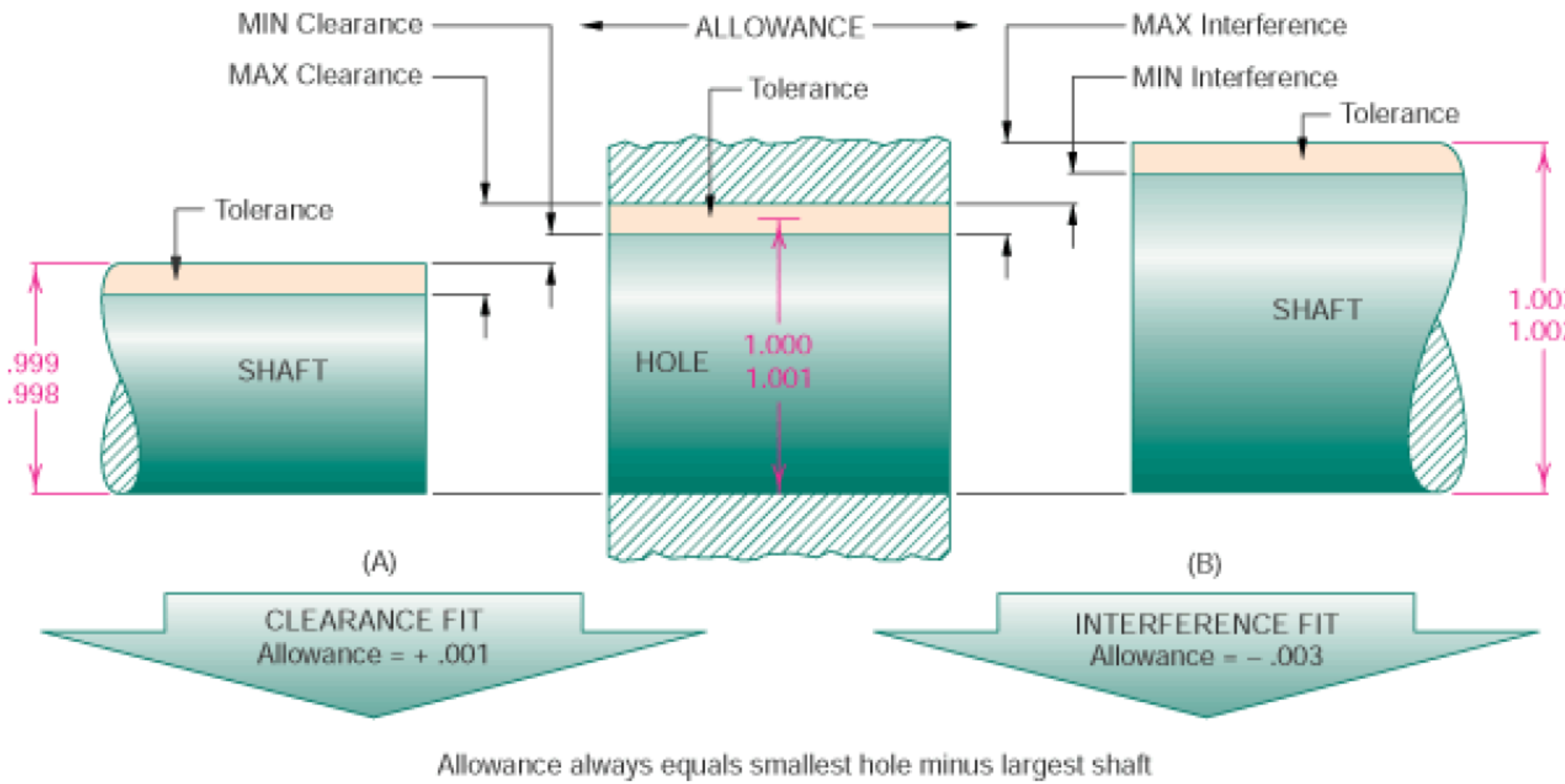
- $C_p = \frac{U-L}{6\sigma}$, measure of the spread of the population about the average
- $C_{pk} = \min\left(C_{pl}, C_{pu}\right)$, measure of both the location and spread of the population
  - $C_{pl} = \frac{\mu-L}{3\sigma}$
  - $C_{pu} = \frac{U-\mu}{3\sigma}$
- $C_c = \max(C_{cl}, C_{cu})$, measure of the location of the average of the population form the target value
  - $C_{cl} = \frac{\tau-\mu}{\tau-L}$
  - $C_{cu} = \frac{\mu-\tau}{U-\tau}$
- $C_{pm} = \frac{U-L}{6\sqrt{\sigma^2+(\mu-\tau)^2}}$, root-mean-square (RMS) deviation index (closely related to a Taguchi quadratic cost function)

Six Sigma

Sigma	Defects per Million	Cost of Poor Quality	
6 Sigma	3.4	<10% of sales	World Class
5 Sigma	233	10-15% of sales	
4 Sigma	6210	15-20% of sales	Industry Average
3 Sigma	66,807	20-30% of sales	
2 Sigma	308,537	30-40% of sales	Noncompetitive
1 Sigma	690,000		

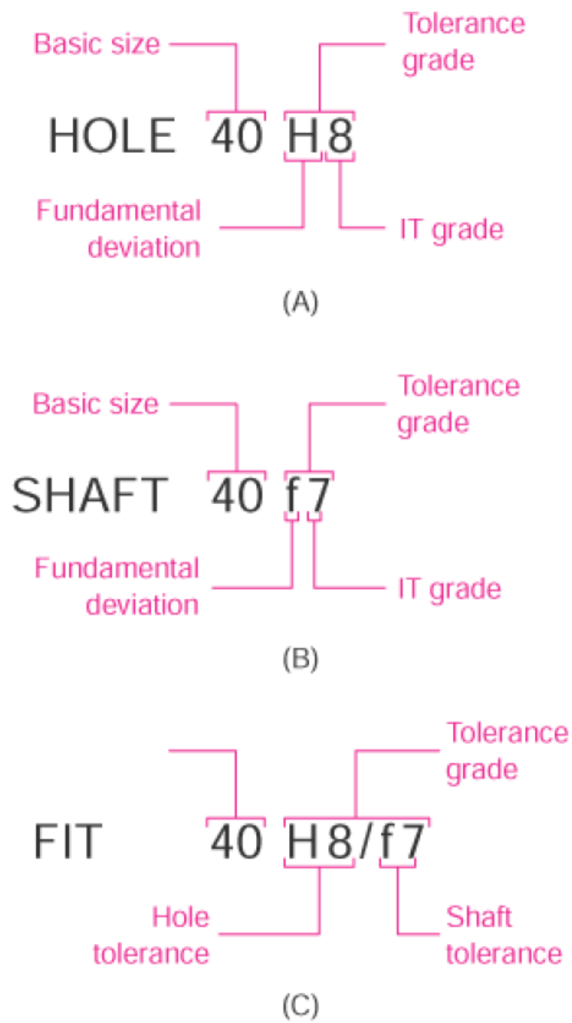
Fits

-

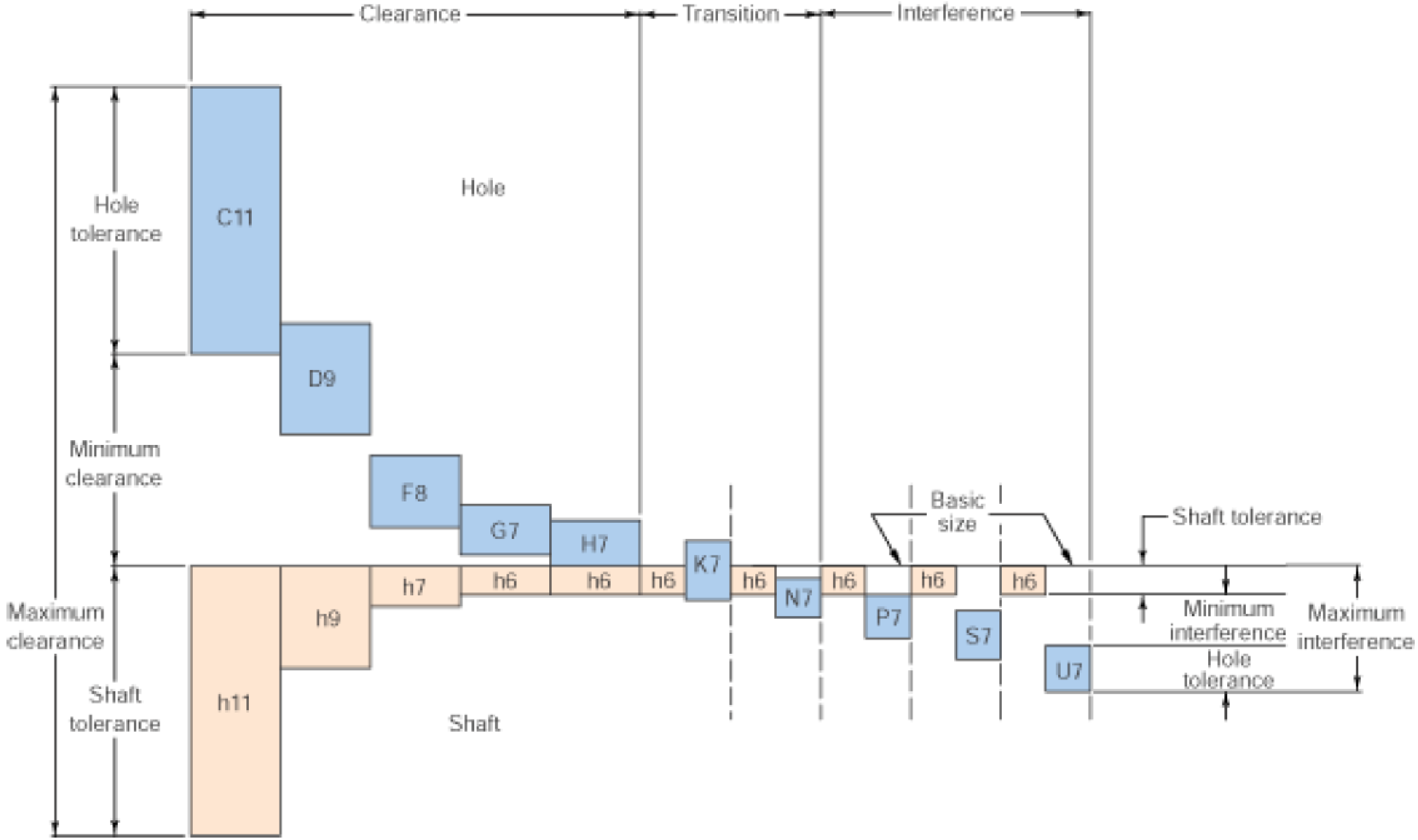


MIN Clearance
MAX Clearance
ALLOWANCE
Tolerance
MAX Interference
MIN Interference
Tolerance
Tolerance
SHAFT
.999
.998
HOLE
1.000
1.001
SHAFT
1.003
1.002
(A)
(B)
CLEARANCE FIT
Allowance = + .001
INTERFERENCE FIT
Allowance = – .003
Allowance always equals smallest hole minus largest shaft

Fits General

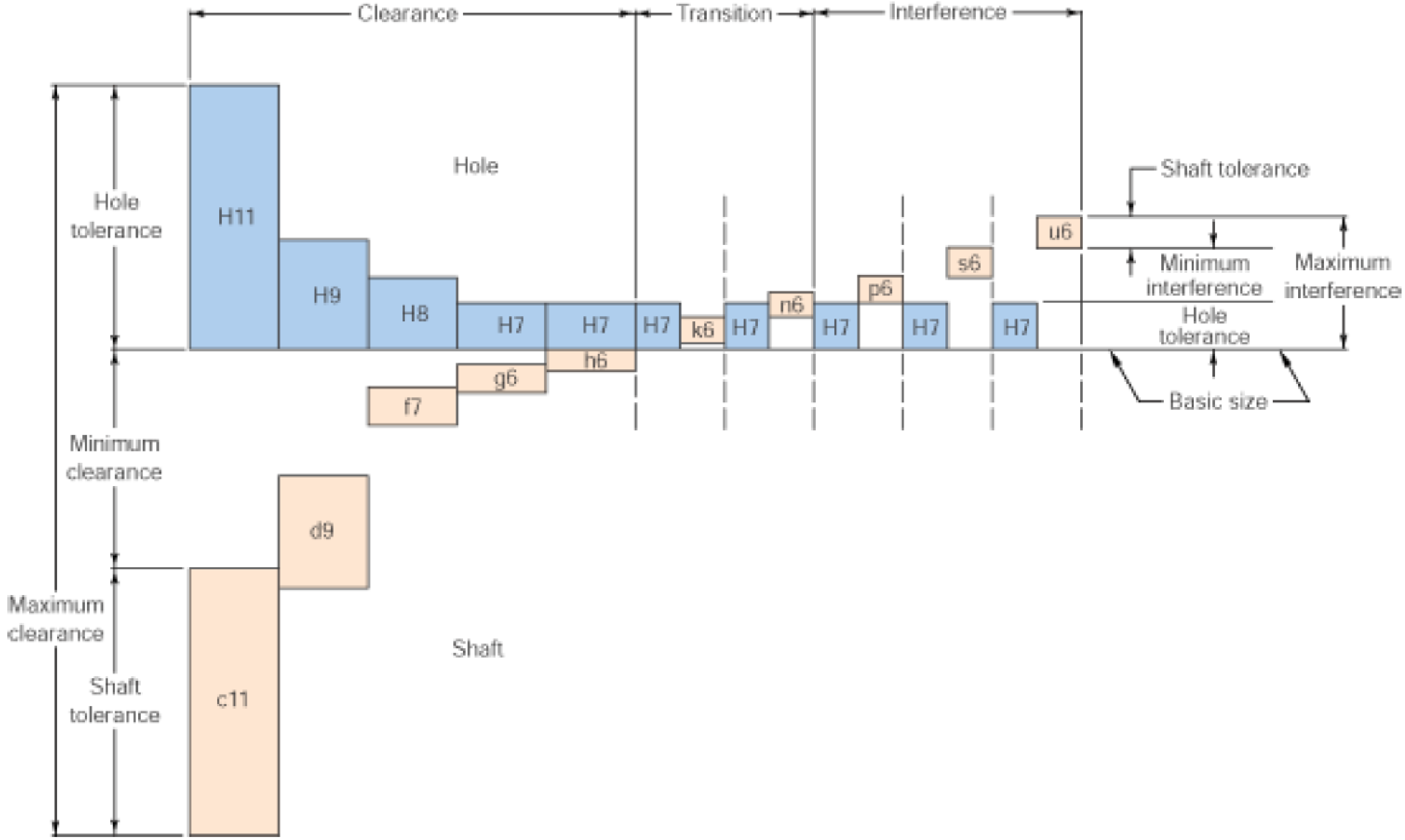


Fits Shaft Driven



Fits Hole Driven

- Hole basis system: fits



Fits ANSI

Table 8a. American National Standard Running and Sliding Fits *ANSI B4.1-1967 (R2009)*

Nominal Size Range, Inches	Class RC 1			Class RC 2			Class RC 3			Class RC 4		
		Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits			Standard Tolerance Limits	
	Clearance[a]	Hole H5	Shaft g4	Clearance[a]	Hole H6	Shaft g5	Clearance[a]	Hole H7	Shaft f6	Clearance[a]	Hole H8	Shaft f7
Over To	Values shown below are in thousandths of an inch											
0 - 0.12	0.1	+0.2	−0.1	0.1	+0.25	−0.1	0.3	+0.4	−0.3	0.3	+0.6	−0.3
	0.45	0	−0.25	0.55	0	−0.3	0.95	0	−0.55	1.3	0	−0.7
0.12 - 0.24	0.15	+0.2	−0.15	0.15	+0.3	−0.15	0.4	+0.5	−0.4	0.4	+0.7	−0.4
	0.5	0	−0.3	0.65	0	−0.35	1.2	0	−0.7	1.6	0	−0.9
0.24 - 0.40	0.2	+0.25	−0.2	0.2	+0.4	−0.2	0.5	+0.6	−0.5	0.5	+0.9	−0.5
	0.6	0	−0.35	0.85	0	−0.45	1.5	0	−0.9	2.0	0	−1.1
0.40 - 0.71	0.25	+0.3	−0.25	0.25	+0.4	−0.25	0.6	+0.7	−0.6	0.6	+1.0	−0.6
	0.75	0	−0.45	0.95	0	−0.55	1.7	0	−1.0	2.3	0	−1.3
0.71 - 1.19	0.3	+0.4	−0.3	0.3	+0.5	−0.3	0.8	+0.8	−0.8	0.8	+1.2	−0.8
	0.95	0	−0.55	1.2	0	−0.7	2.1	0	−1.3	2.8	0	−1.6
1.19 - 1.97	0.4	+0.4	−0.4	0.4	+0.6	−0.4	1.0	+1.0	−1.0	1.0	+1.6	−1.0
	1.1	0	−0.7	1.4	0	−0.8	2.6	0	−1.6	3.6	0	−2.0
1.97 - 3.15	0.4	+0.5	−0.4	0.4	+0.7	−0.4	1.2	+1.2	−1.2	1.2	+1.8	−1.2
	1.2	0	−0.7	1.6	0	−0.9	3.1	0	−1.9	4.2	0	−2.4
3.15 - 4.73	0.5	+0.6	−0.5	0.5	+0.9	−0.5	1.4	+1.4	−1.4	1.4	+2.2	−1.4
	1.5	0	−0.9	2.0	0	−1.1	3.7	0	−2.3	5.0	0	−2.8
4.73 - 7.09	0.6	+0.7	−0.6	0.6	+1.0	−0.6	1.6	+1.6	−1.6	1.6	+2.5	−1.6
	1.8	0	−1.1	2.3	0	−1.3	4.2	0	−2.6	5.7	0	−3.2
7.09 - 9.85	0.6	+0.8	−0.6	0.6	+1.2	−0.6	2.0	+1.8	−2.0	2.0	+2.8	−2.0
	2.0	0	−1.2	2.6	0	−1.4	5.0	0	−3.2	6.6	0	−3.8
9.85 - 12.41	0.8	+0.9	−0.8	0.8	+1.2	−0.8	2.5	+2.0	−2.5	2.5	+3.0	−2.5
	2.3	0	−1.4	2.9	0	−1.7	5.7	0	−3.7	7.5	0	−4.5
12.41 - 15.75	1.0	+1.0	−1.0	1.0	+1.4	−1.0	3.0	+2.2	−3.0	3.0	+3.5	−3.0
	2.7	0	−1.7	3.4	0	−2.0	6.6	0	−4.4	8.7	0	−5.2
15.75 - 19.69	1.2	+1.0	−1.2	1.2	+1.6	−1.2	4.0	+2.5	−4.0	4.0	+4.0	−4.0
	3.0	0	−2.0	3.8	0	−2.2	8.1	0	−5.6	10.5	0	−6.5

Fits ISO

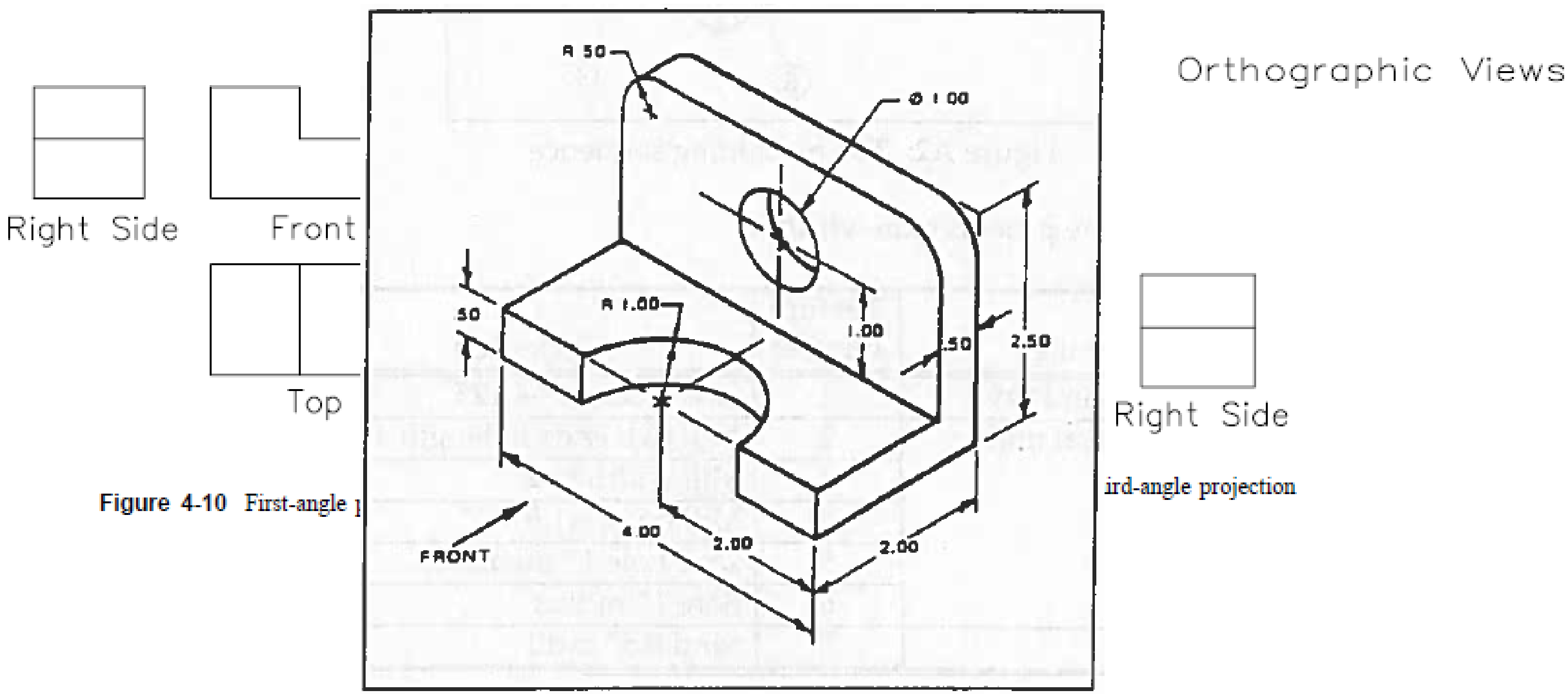
Table 1. Description of Preferred Fits

	ISO SYMBOL		DESCRIPTION	
	Hole Basis	Shaft Basis		
Clearance Fits	H11/c11	C11/h11	*Loose running* fit for wide commercial tolerances or allowances on external members.	↑ More Clearance
	H9/d9	D9/h9	*Free running* fit not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.	
	H8/f7	F8/h7	*Close Running* fit for running on accurate machines and for accurate moderate speeds and journal pressures.	
	H7/g6	G7/h6	*Sliding fit* not intended to run freely, but to move and turn freely and locate accurately.	
	H7/h6	H7/h6	*Locational clearance* fit provides snug fit for locating stationary parts; but can be freely assembled and disassembled.	
Transition Fits	H7/k6	K7/h6	*Locational transition* fit for accurate location, a compromise between clearance and Interference.	
	H7/n6	N7/h6	*Locational transition* fit for more accurate location where greater interference is permissible.	
Interference Fits	H7/p6[a]	P7/h6	*Locational interference* fit for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements.	More Interference ↓
	H7/s6	S7/h6	*Medium drive* fit for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.	
	H7/u6	U7/h6	*Force* fit suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.	

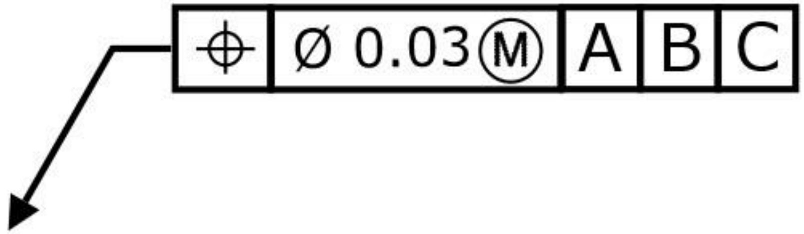
[a] Transition fit for basic sizes in range from 0 through 3 mm.

Dimensioning

- Complete information about both *size* and *shape*
  - Size: Dimensions
  - Shape: Drawings (Usually orthographic)



GD&T

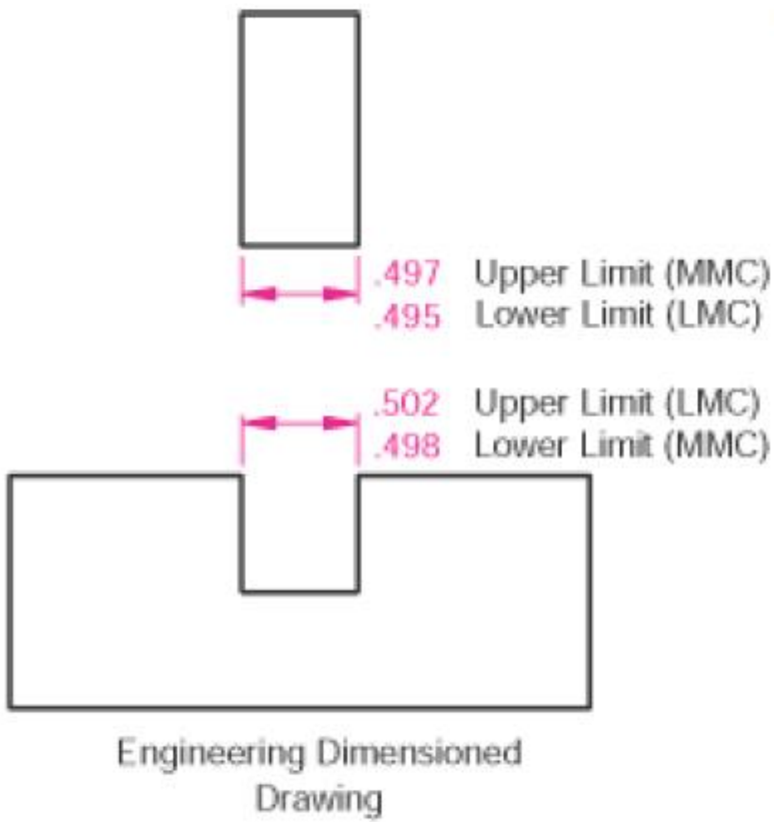


Definitions

- Maximum Material Condition (MMC)
  – The dimension tolerance limit that produces a part that contains the most amount of material for that dimension.

- Least Material Condition (LMC)
  – The dimension tolerance limit that produces a part that contains the least amount of material possible for that dimension.

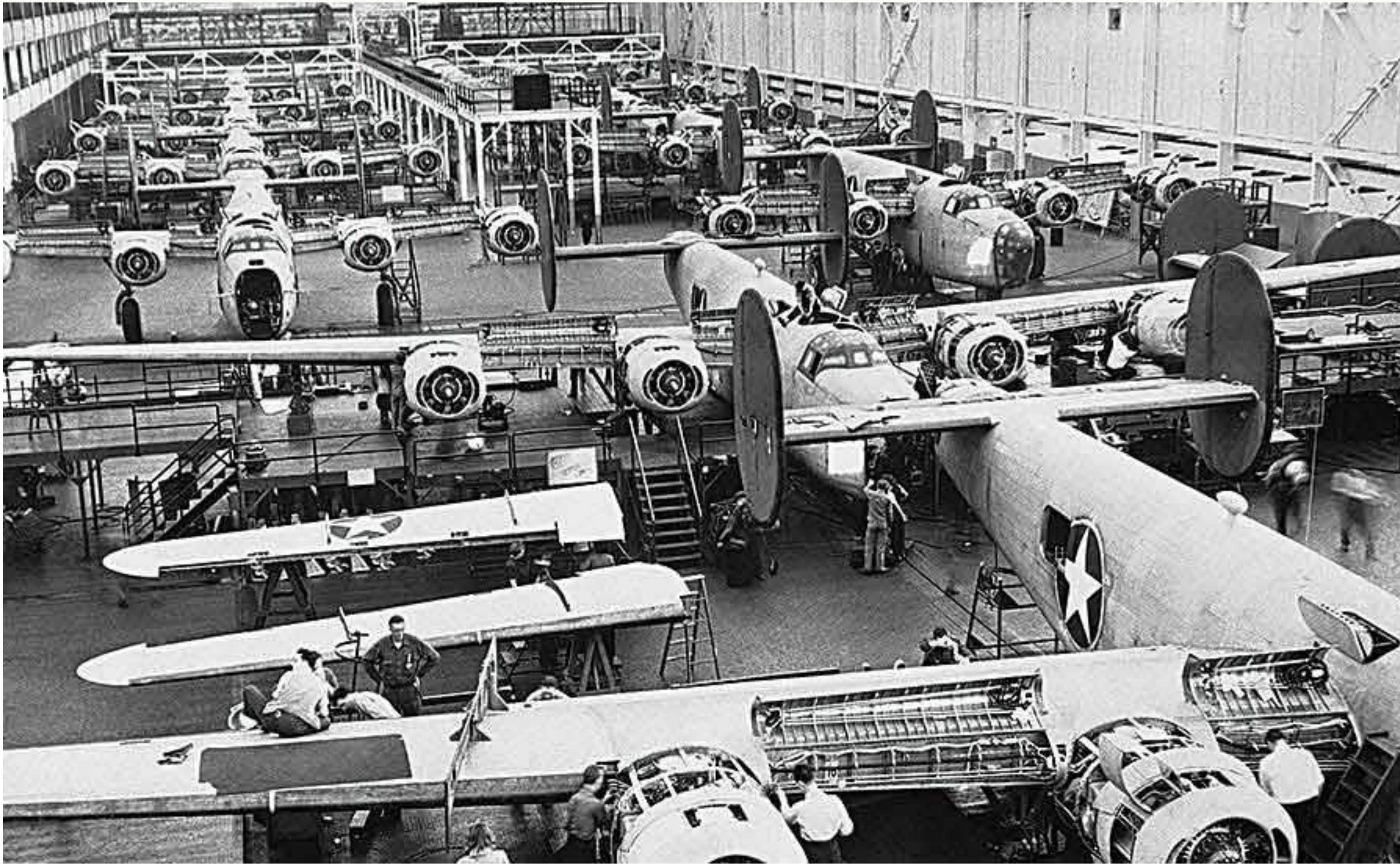
Definitions



Tolerancing Fits

- Clearance
  - Mating parts always have space or clearance when assembled
- Interference
  - Mating parts always interfere when assembled
- Transition
  - Mating parts will sometimes be interference and sometimes be clearance when assembled

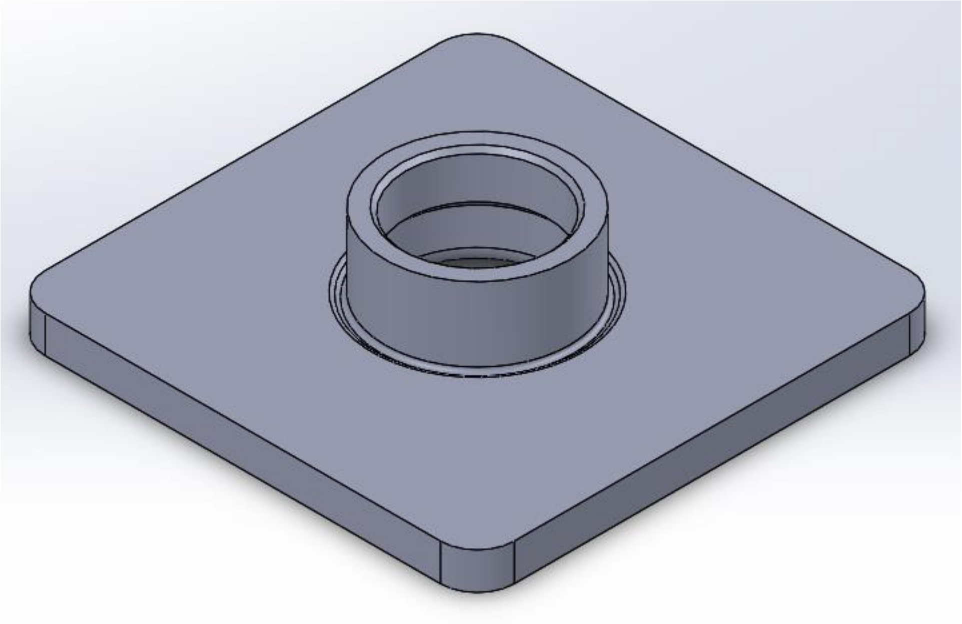
Why?



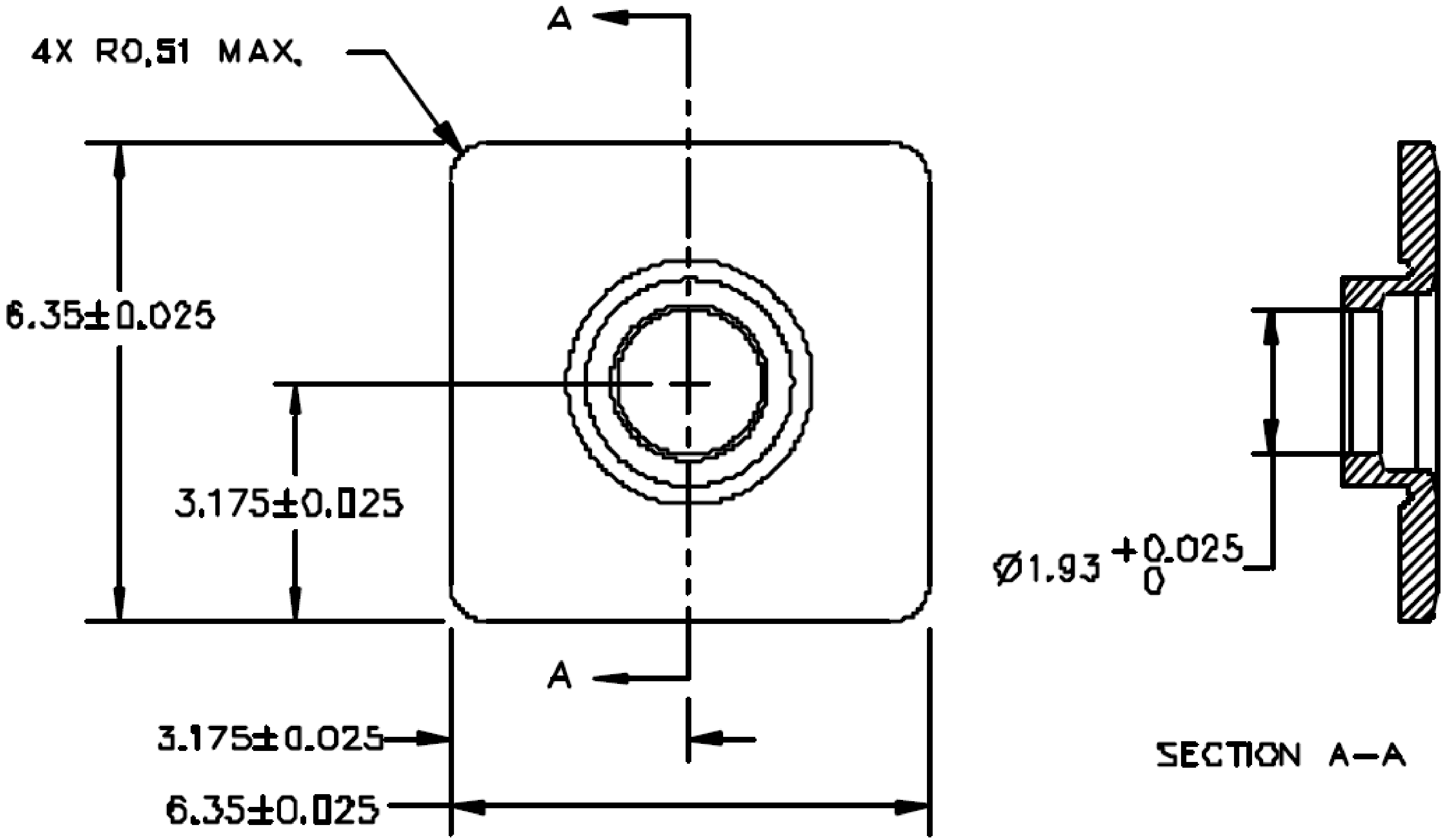
Motivation

Design Intent

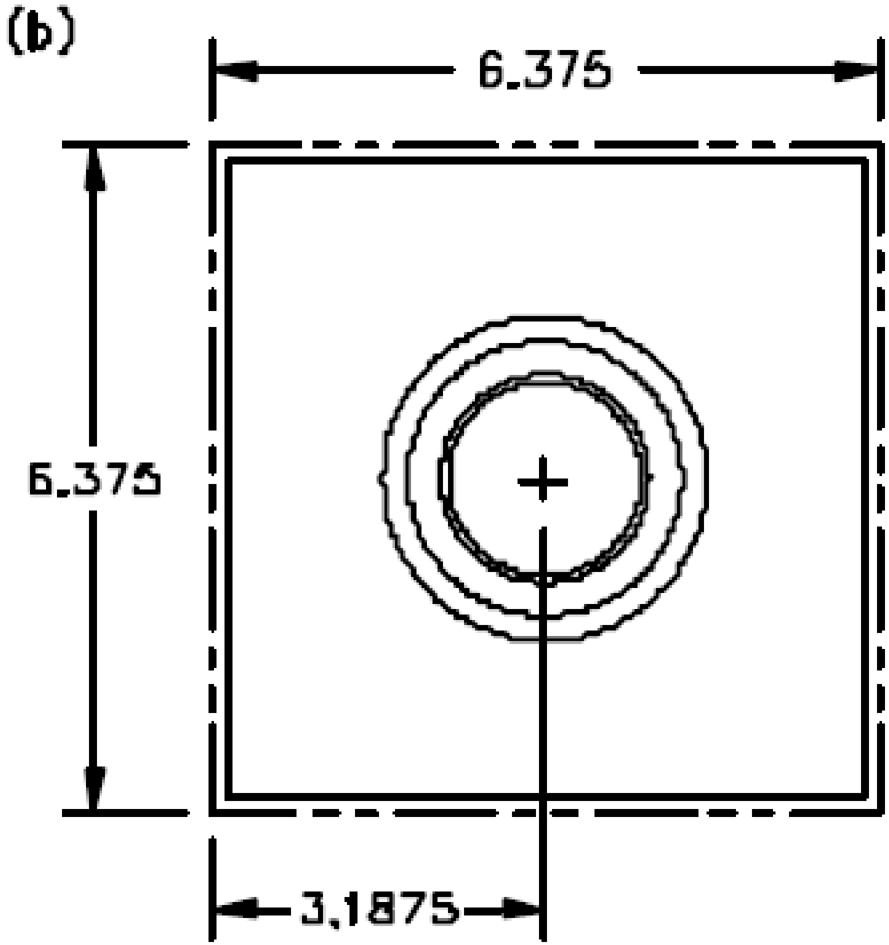
- External boundary 6.35 mm ± 0.025 mm “square”
- Hub inside diameter on “center” of the square within ± 0.025 mm



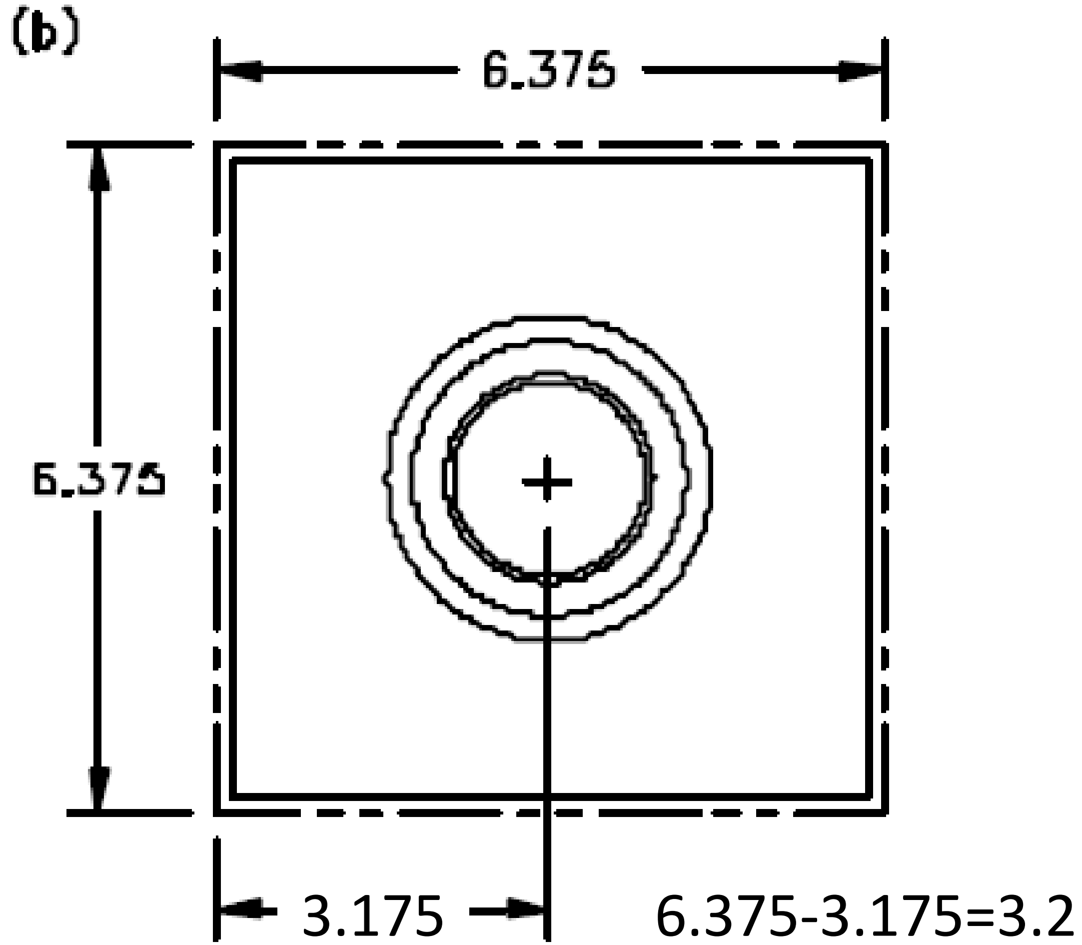
Linear Strategy



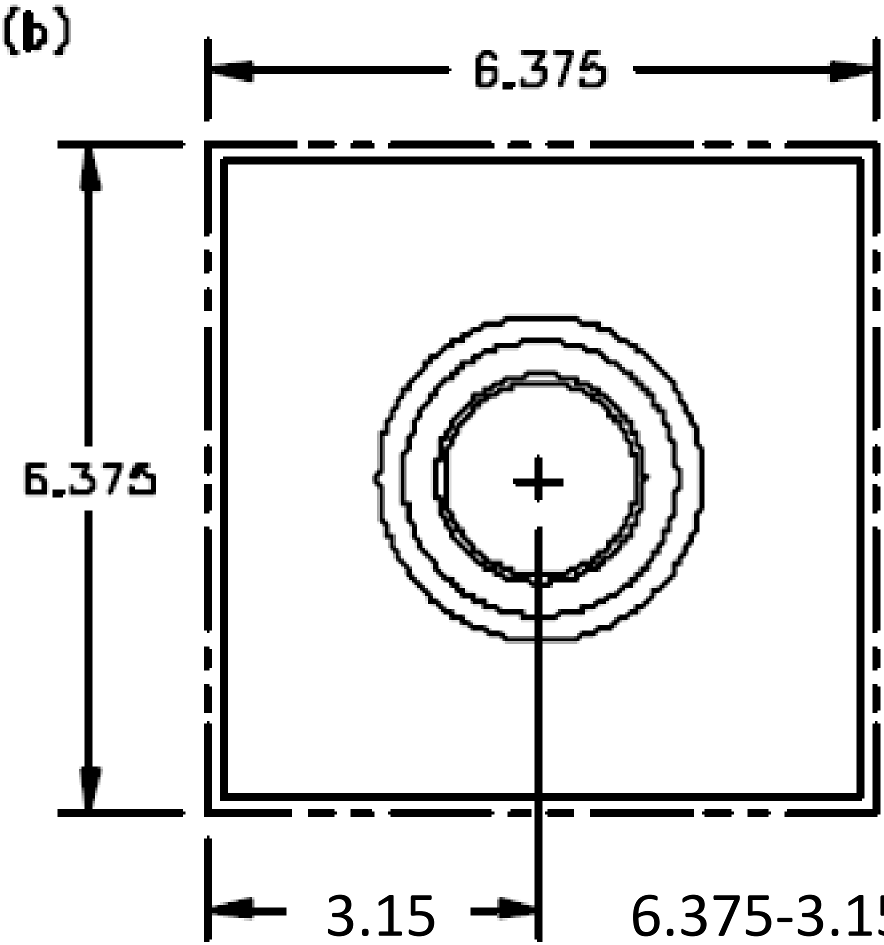
Linear Strategy



Linear Strategy

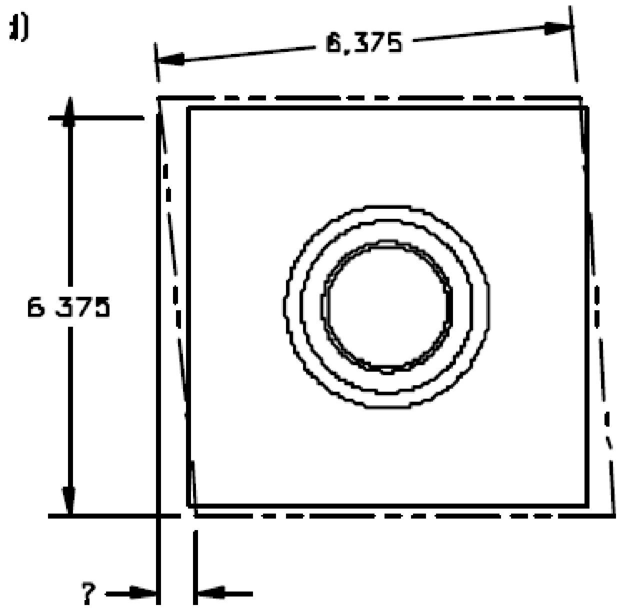


Linear Strategy



6.375-3.15=3.225

Linear Strategy



- **ANSI:** Rule #1 (Taylor Principle) - When only a size tolerance is specified for an individual feature of size the form of this feature shall not extend beyond a boundary (envelope) of perfect form at maximum material condition (MMC).

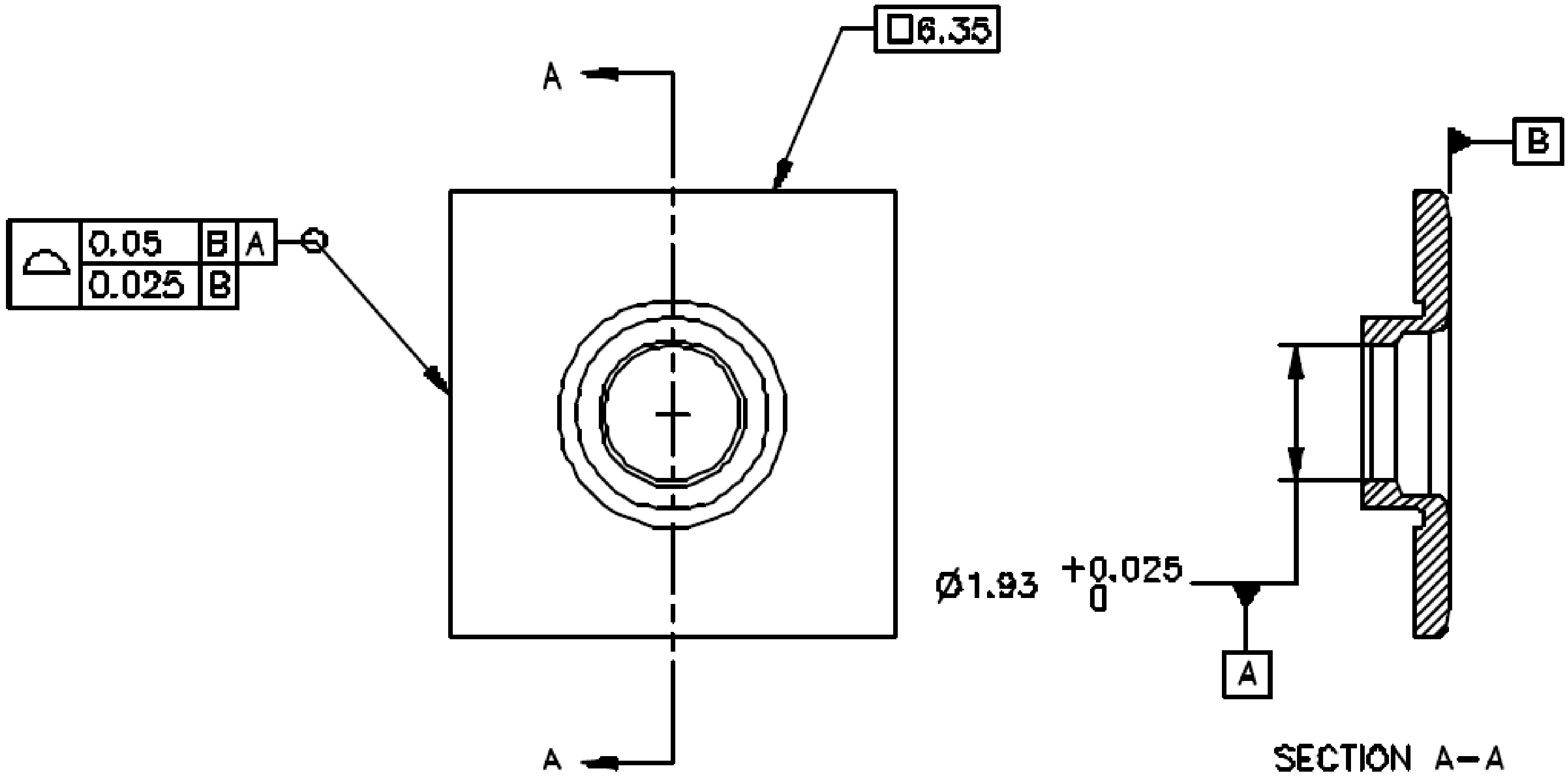
- **ISO:** Principle of Independence

Linear Strategy

- Paragraph 2.7.3 of Y14.5 addresses the "relationship between individual features," and states:

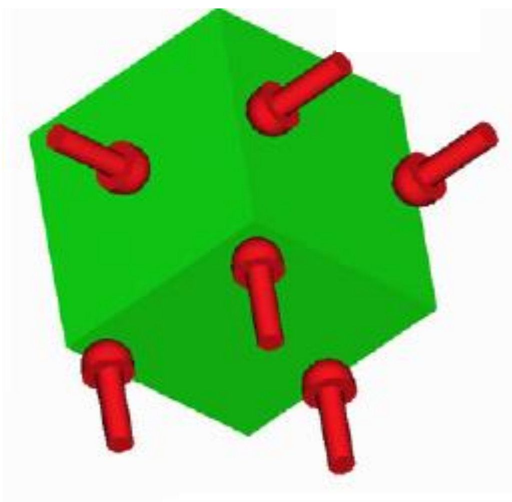
  The limits of size do not control the orientation or location relationship between individual features. Features shown perpendicular, coaxial, or symmetrical to each other must be controlled for location or orientation to avoid incomplete drawing requirements.

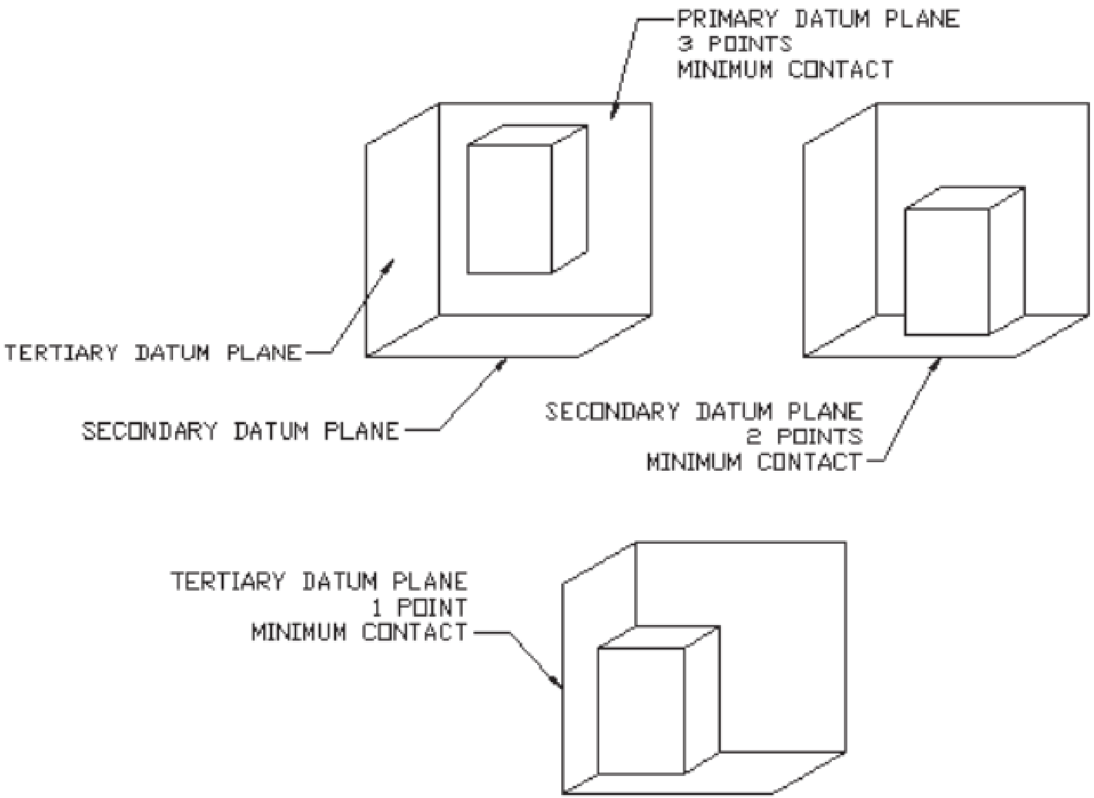
Full Geometric



Datum

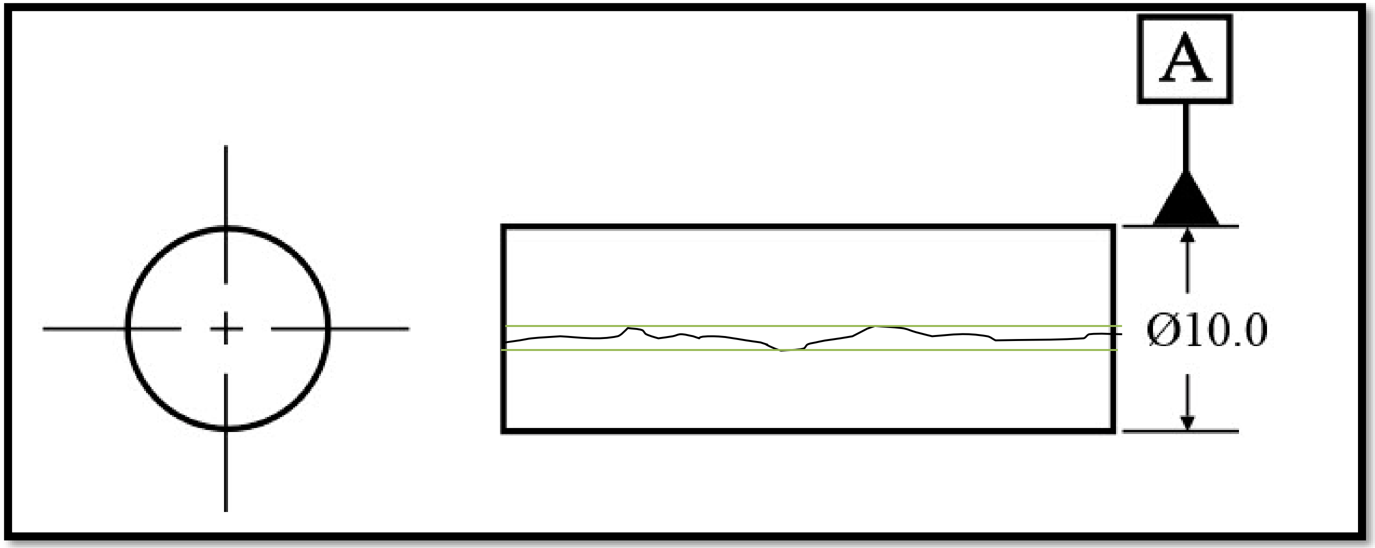
6 DOF



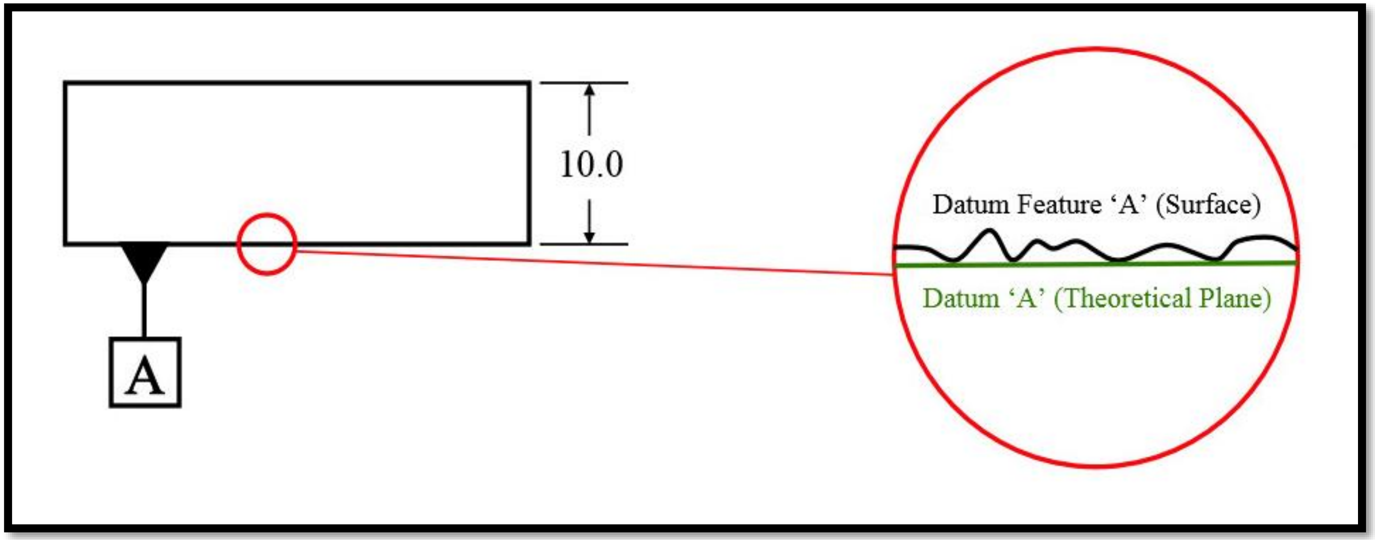

PRIMARY DATUM PLANE
3 POINTS
MINIMUM CONTACT
TERTIARY DATUM PLANE
SECONDARY DATUM PLANE
SECONDARY DATUM PLANE
2 POINTS
MINIMUM CONTACT
TERTIARY DATUM PLANE
1 POINT
MINIMUM CONTACT

Theory Vs Reality

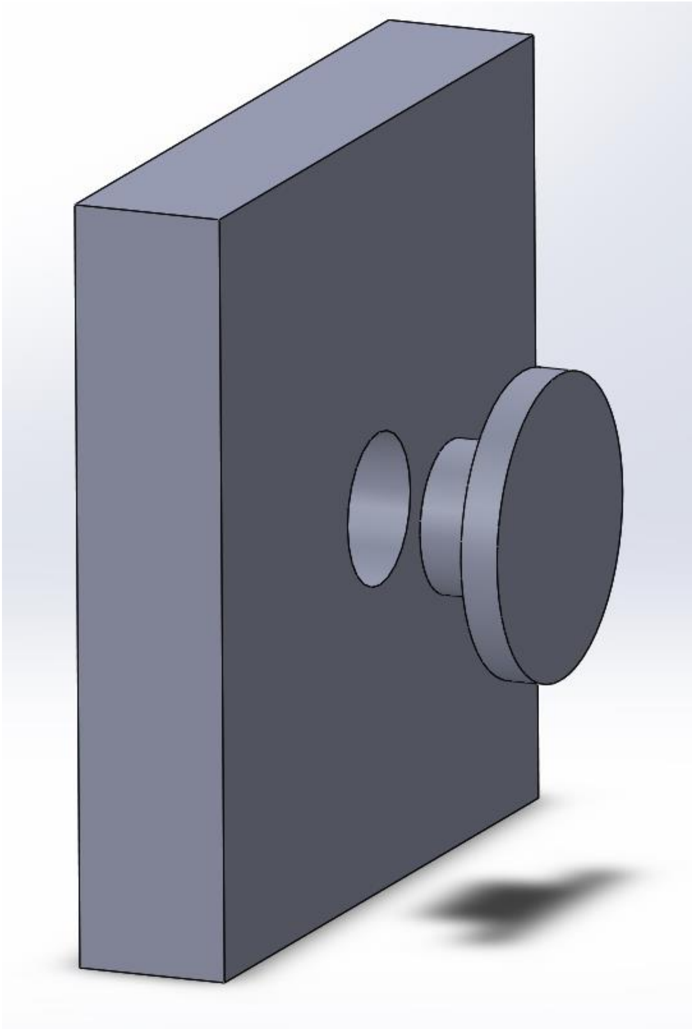
Axis

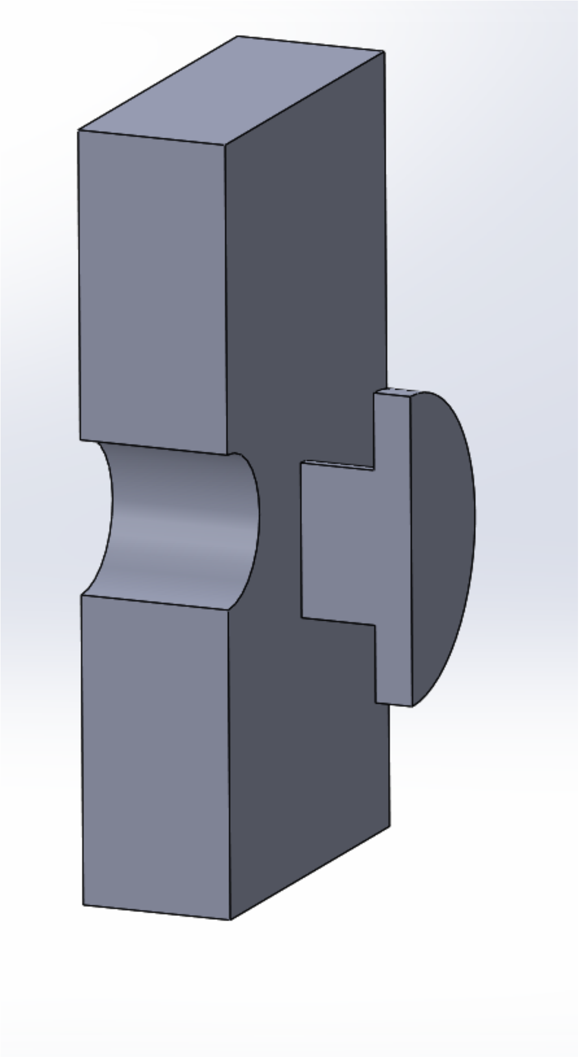


Plane

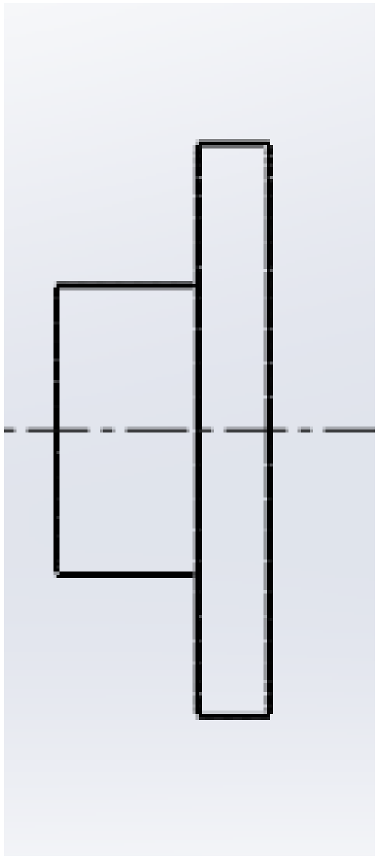


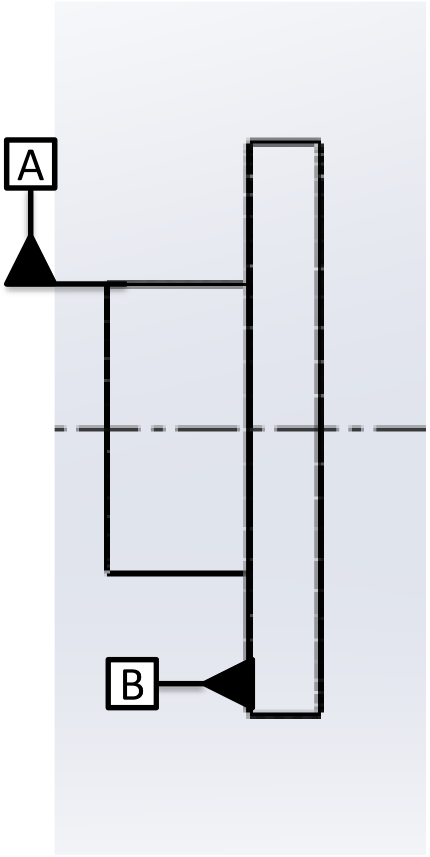
Datums and Design Intent

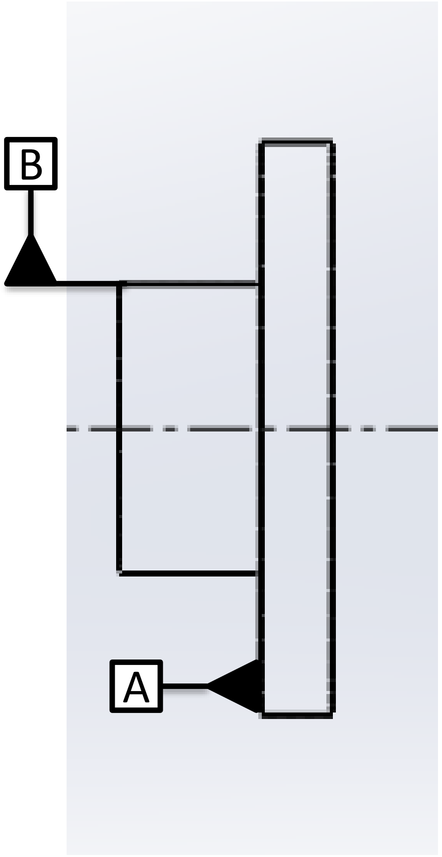




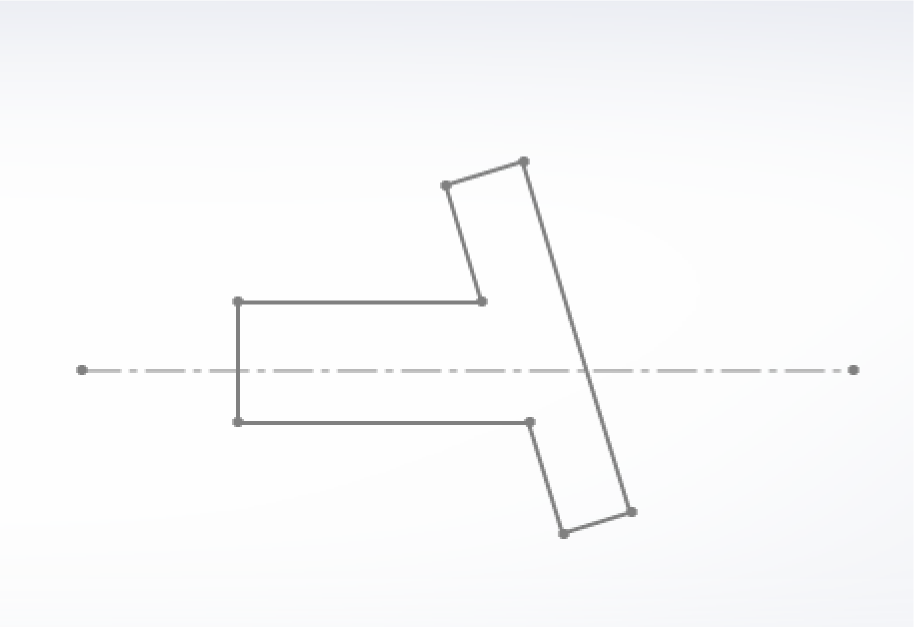
Datum Choices



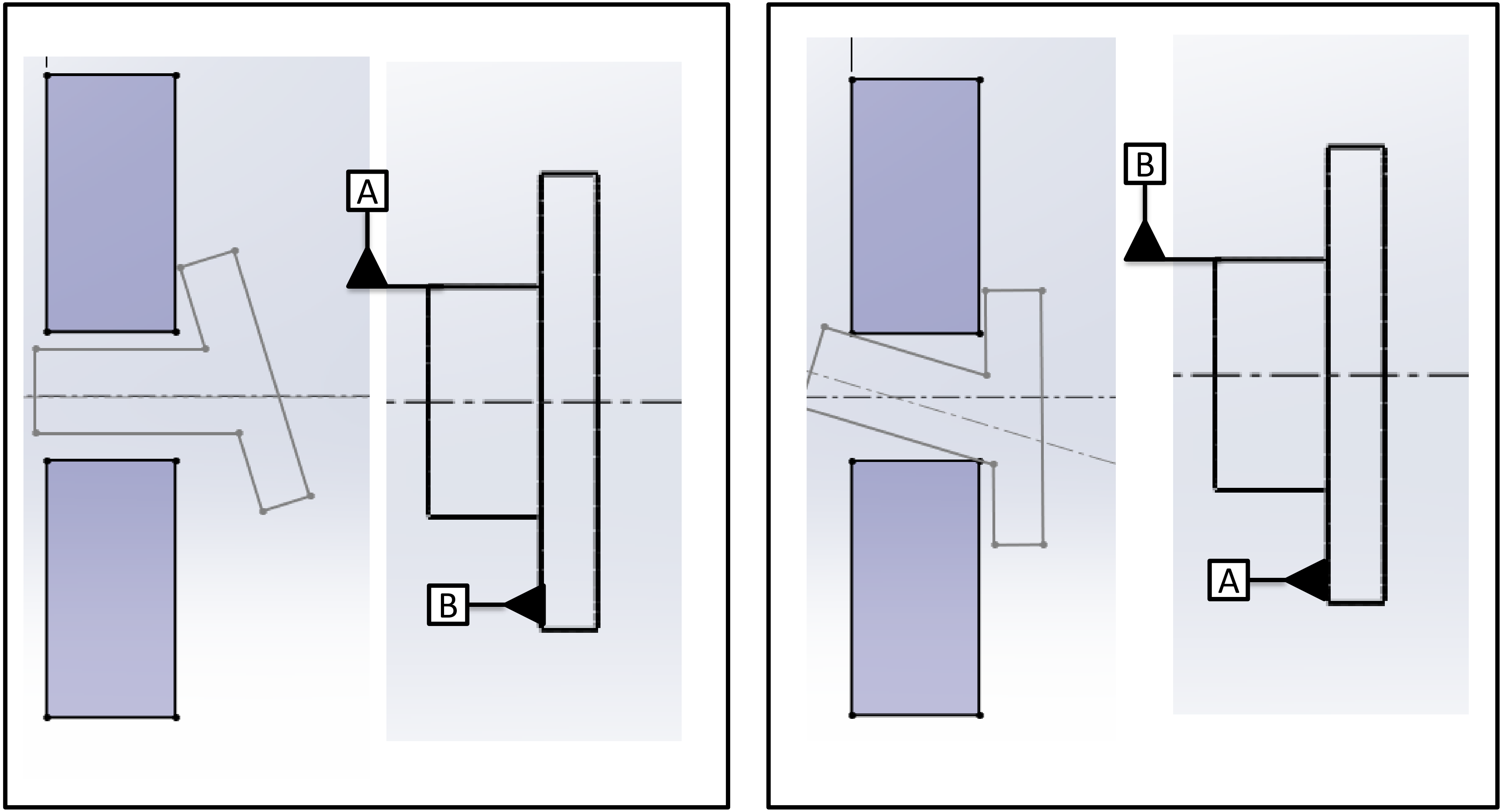




As built



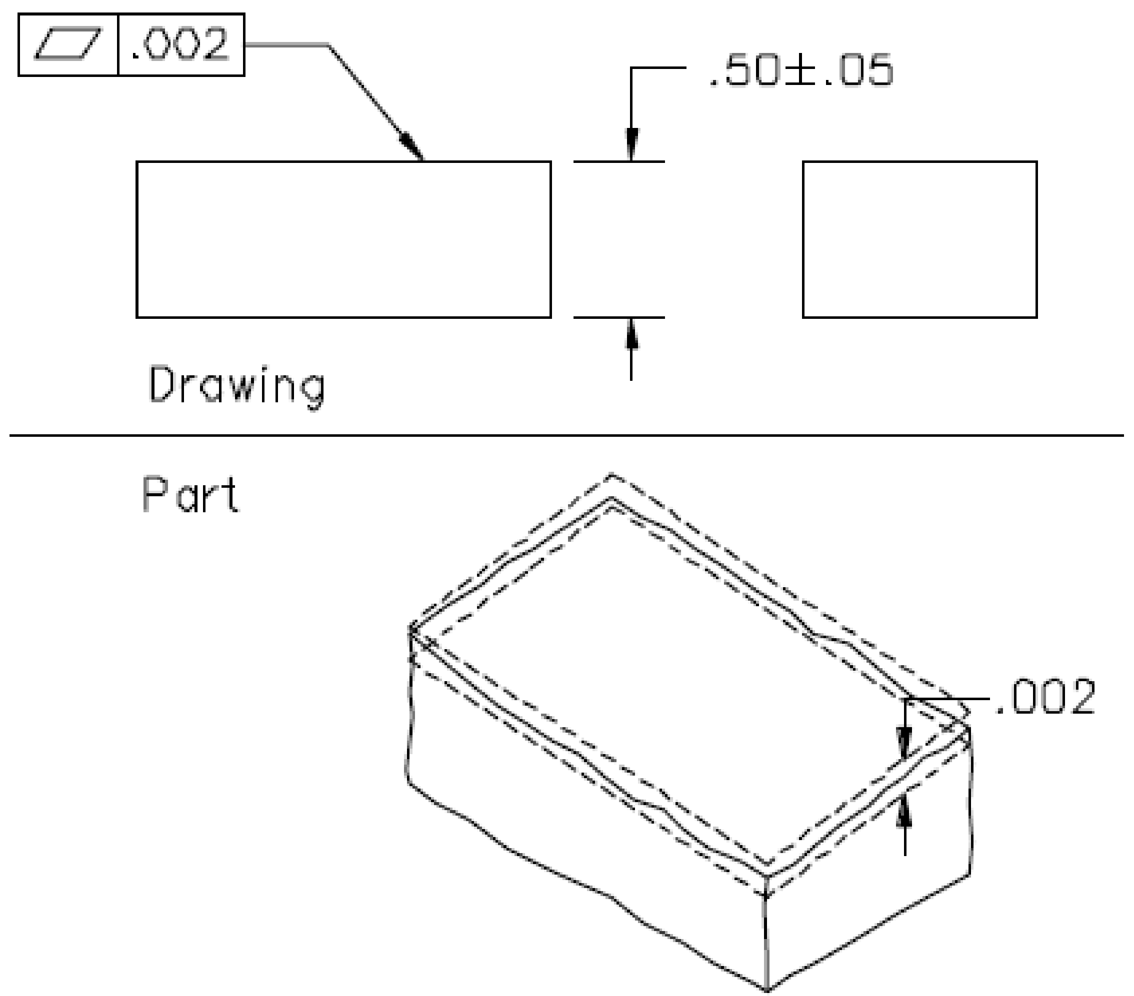
Datum Intent



Some Controls

CHARACTERISTIC	SYMBOL	TYPE OF FEATURE CONTROLLED	FEATURE CONTROL FRAM PLACEMENT OPTIONS (SEE LEGEND)	BOUNDARY/TOL ZONE SHAPE MODIFIER	TOLERANCE MODIFIABLE TO MMC OR LMC	NUMBER OF DATUM REFERENCES ALLOWED	MMC/LMC ALLOWED FOR DATUM REFERENCE(S)	BASIC DIMENSION REQD
STRAIGHTNESS	—	CYL-SURFACE ELEMENTS	b			0		
		CYL-DERIVED MEDIAN LINE	a, d	Ø	✓	0		
		PLANE-LINE ELEMENTS	b, c			0,1		
FLATNESS	▱	PLANE	b, c			0		
		WIDTH-DERIVED MEDIAN PLANE	a, d		✓	0		
CIRCULARITY	○	REVOLUTE, SPHERE	a, b, d			0		
CYLINDRICITY	⌭	CYLINDER	a, b, d			0		
PROFILE OF A LINE	⌒	ALL	b			0–3	✓	✓
PROFILE OF A SURFACE	⌓	REVOLUTE	b			0–3	✓	✓
		OTHER (NON-REVOLUTE)	b			0–3	✓	✓
		COPLANARITY OF PLANES	b			0		
PERPENDICULARITY PARALLELISM	⊥ //	PLANE (INCL LINE ELEMENTS)	b, c			1–3	✓	
		CYLINDER	a, d	Ø	✓	1–3	✓	
		WIDTH	a, d		✓	1–3	✓	
		REVOLUTE-RADIAL ELEMENT	b, c			1–3	✓	
ANGULARITY	∠	PLANE (INCL LINE ELEMENTS)	b ,c			1–3	✓	✓
		CYLINDER	a, d	Ø	✓	1–3	✓	✓
		WIDTH	a, d		✓	1–3	✓	✓
		REVOLUTE-RADIAL ELEMENT	b, c			1–3	✓	✓
POSITION	⌖	CYLINDER	a, d	Ø	✓	1–3	✓	✓
		WIDTH	a, d		✓	1–3	✓	✓
		SPHERE	a, d	SØ	✓	1–3	✓	✓
CONCENTRICITY	◎	ALL NON-SPHERICAL	a, b, d	Ø		1–3		
		SPHERE	a, b, d	SØ		1–3		
SYMMETRY	⌯	OPPOSED POINTS	a, d			1–3		
CIRCULAR RUNOUT	↗	REVOLUTE	a, b, d			1–2		
TOTAL RUNOUT	⌰	CYLINDER	a, b, d			1–2		
		PLANE PERP TO AXIS	b, c			1–2		

Flatness



Circularity

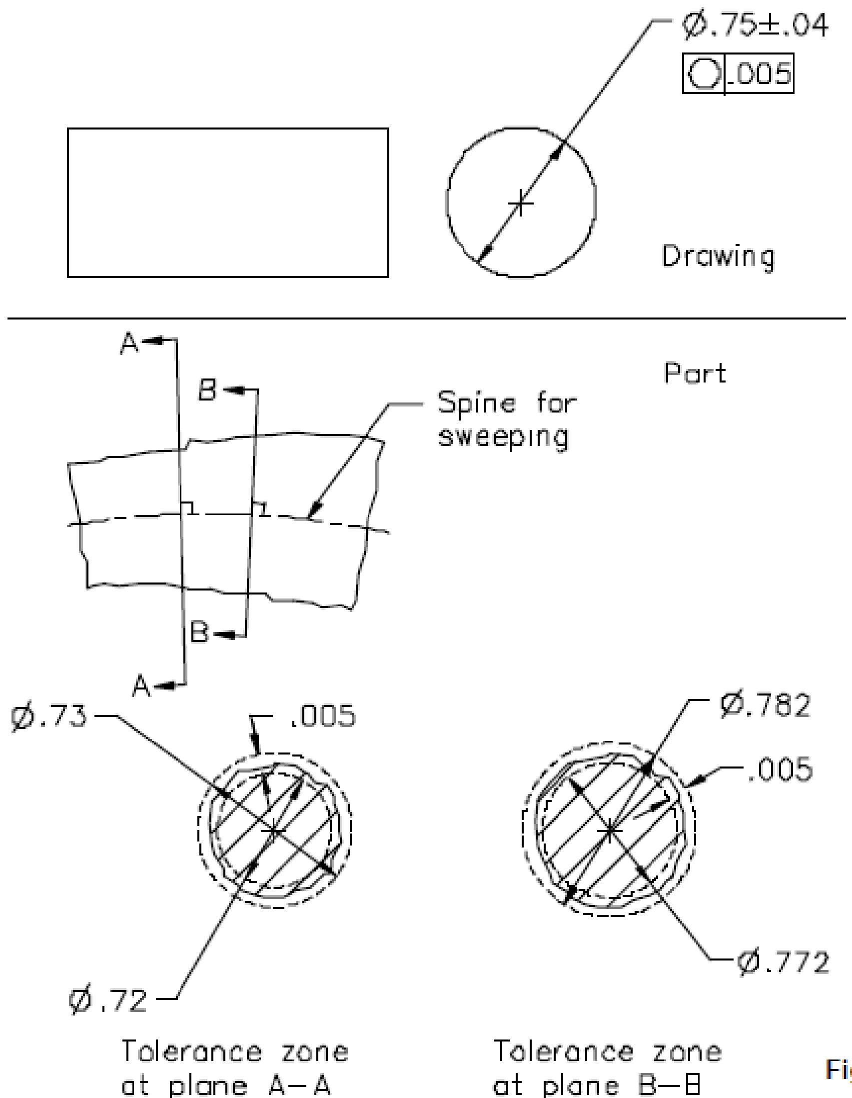
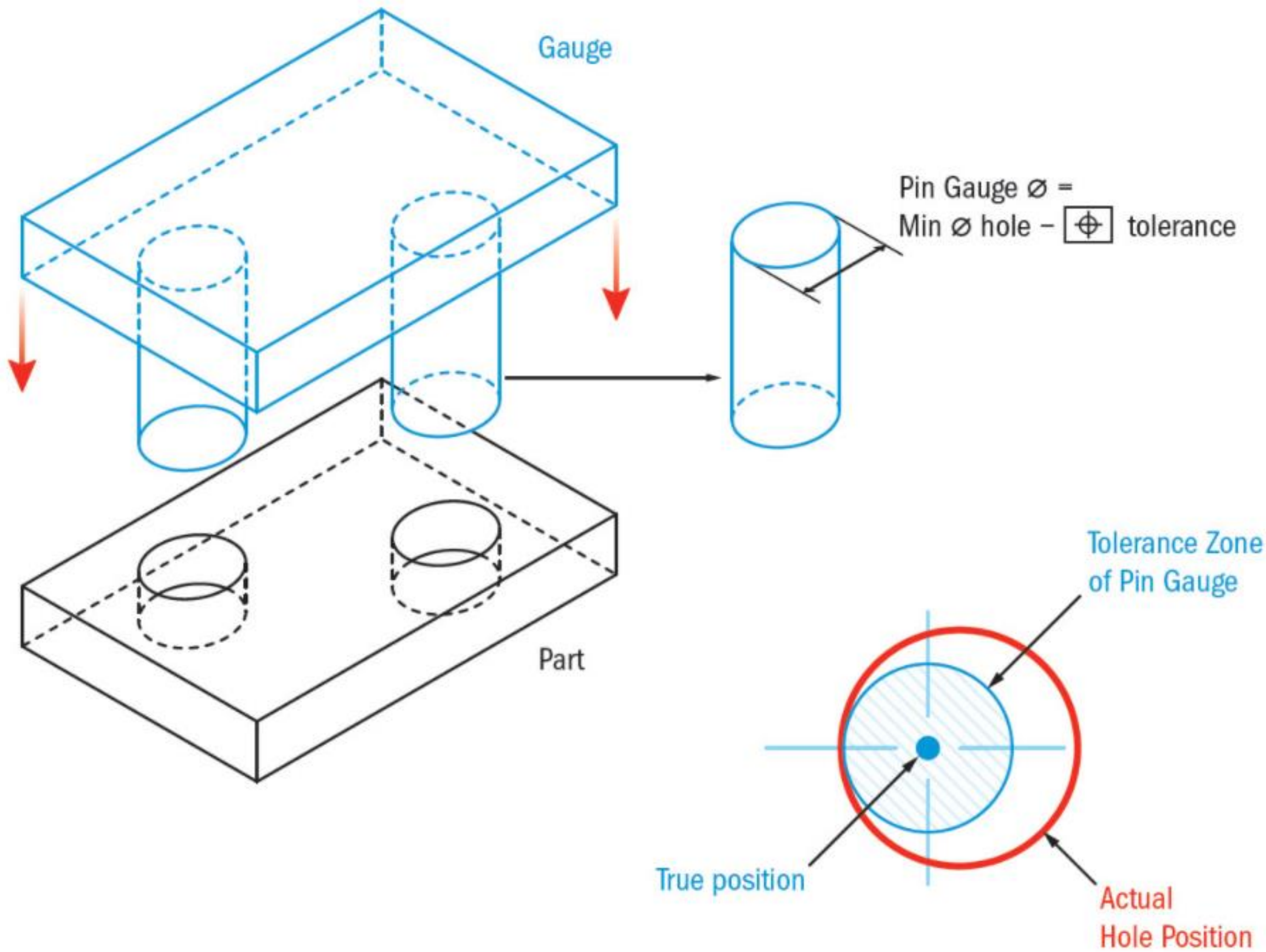


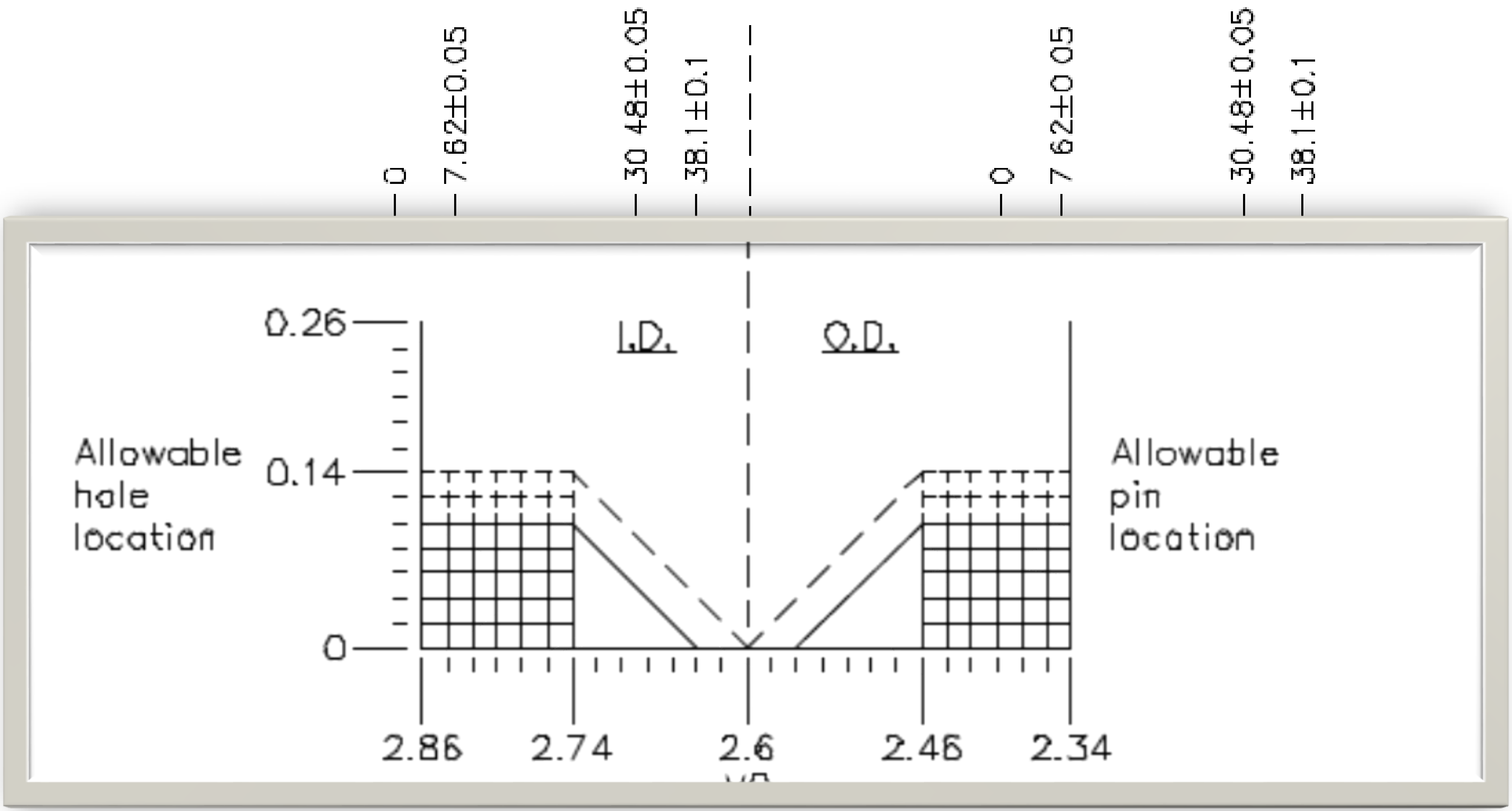
Fig
non

Location

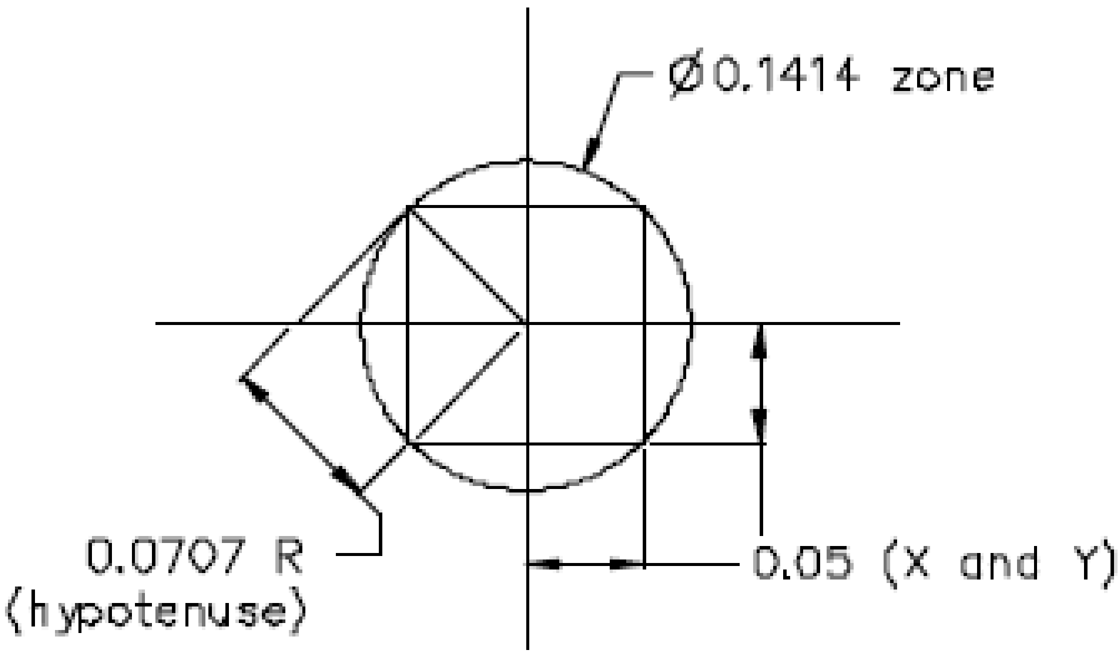


Gauge
Pin Gauge ⌀ =
Min ⌀ hole – ⌖ tolerance
Part
Tolerance Zone
of Pin Gauge
True position
Actual
Hole Position

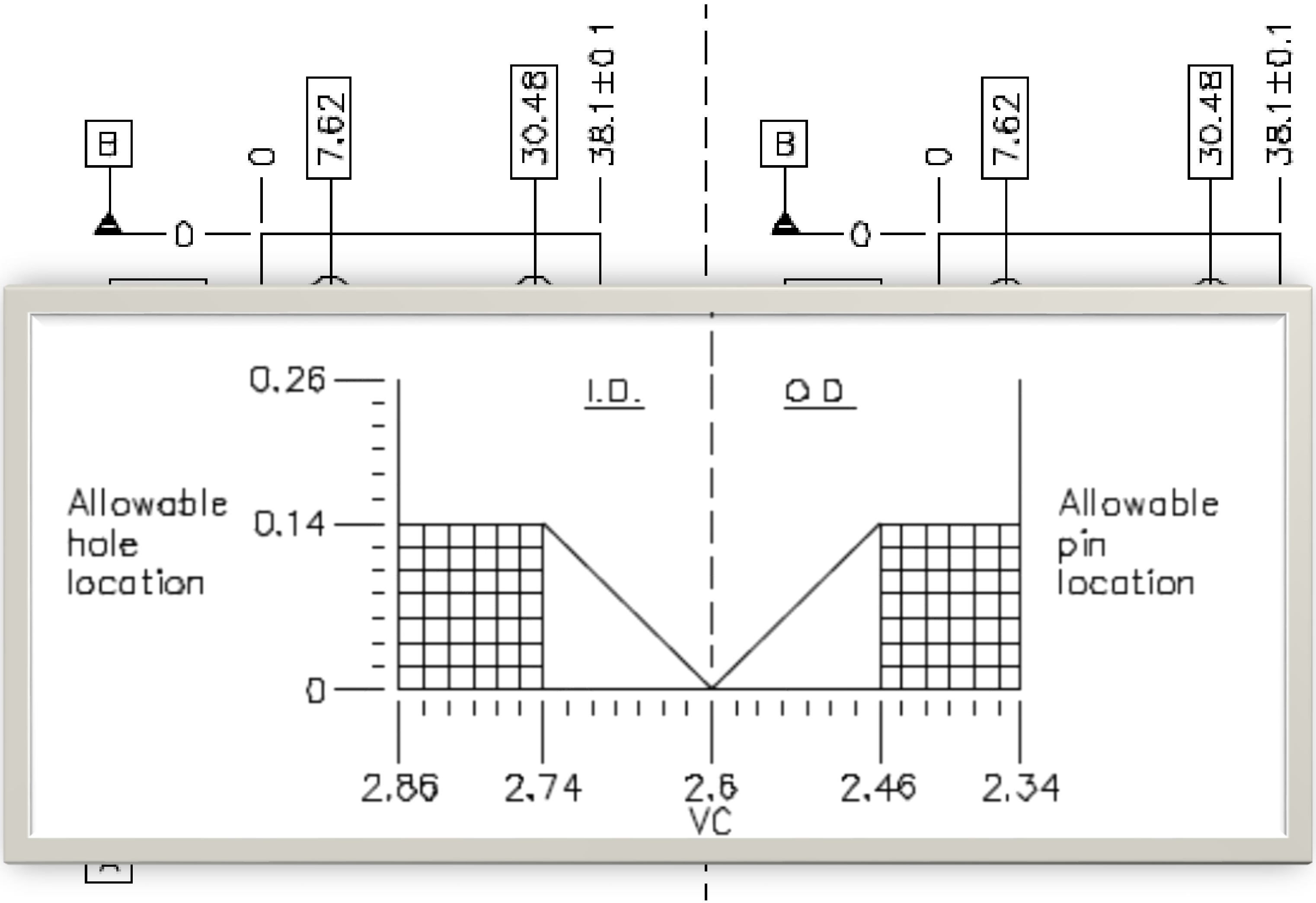
4 Pin Example



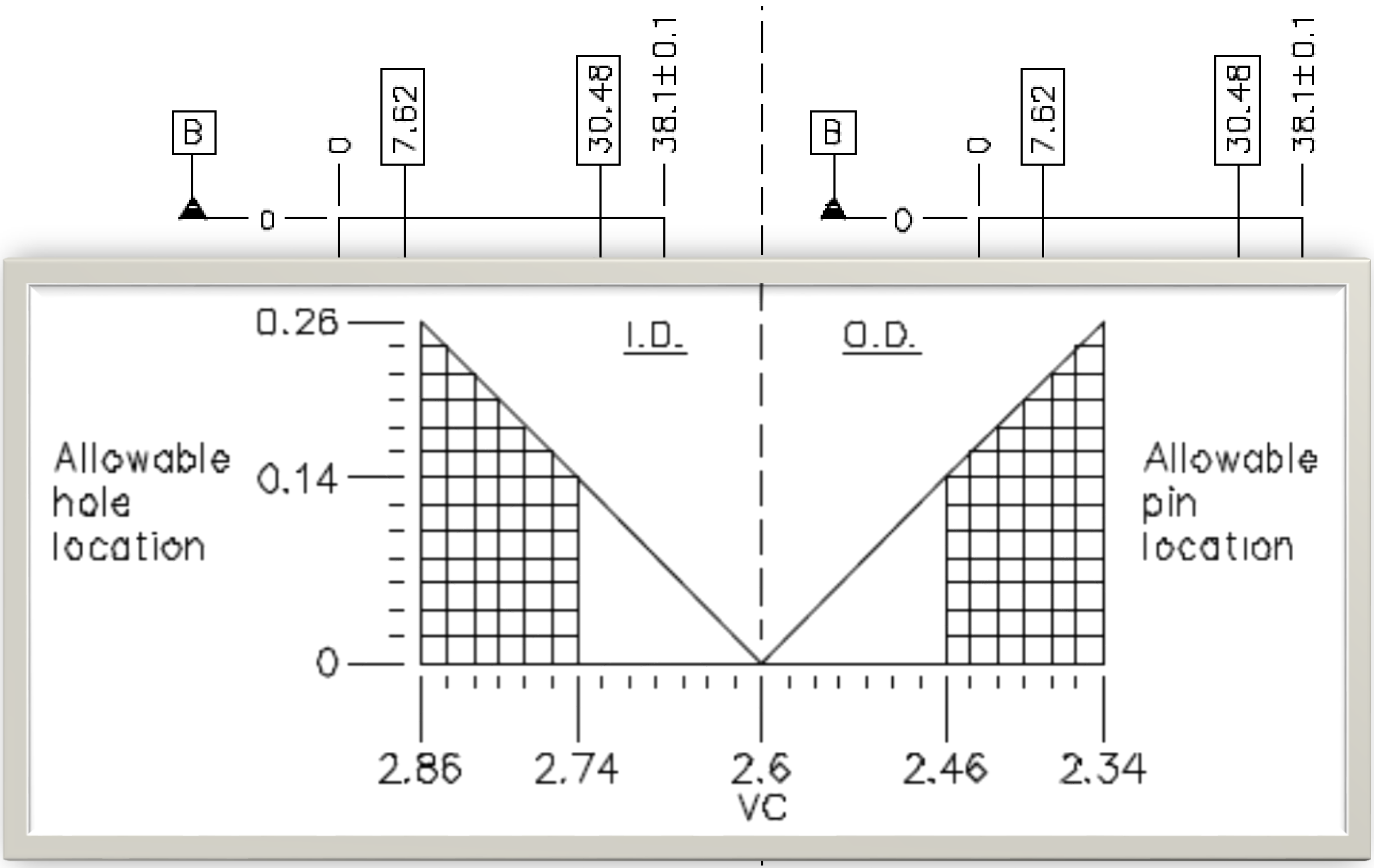
Tolerance Zone



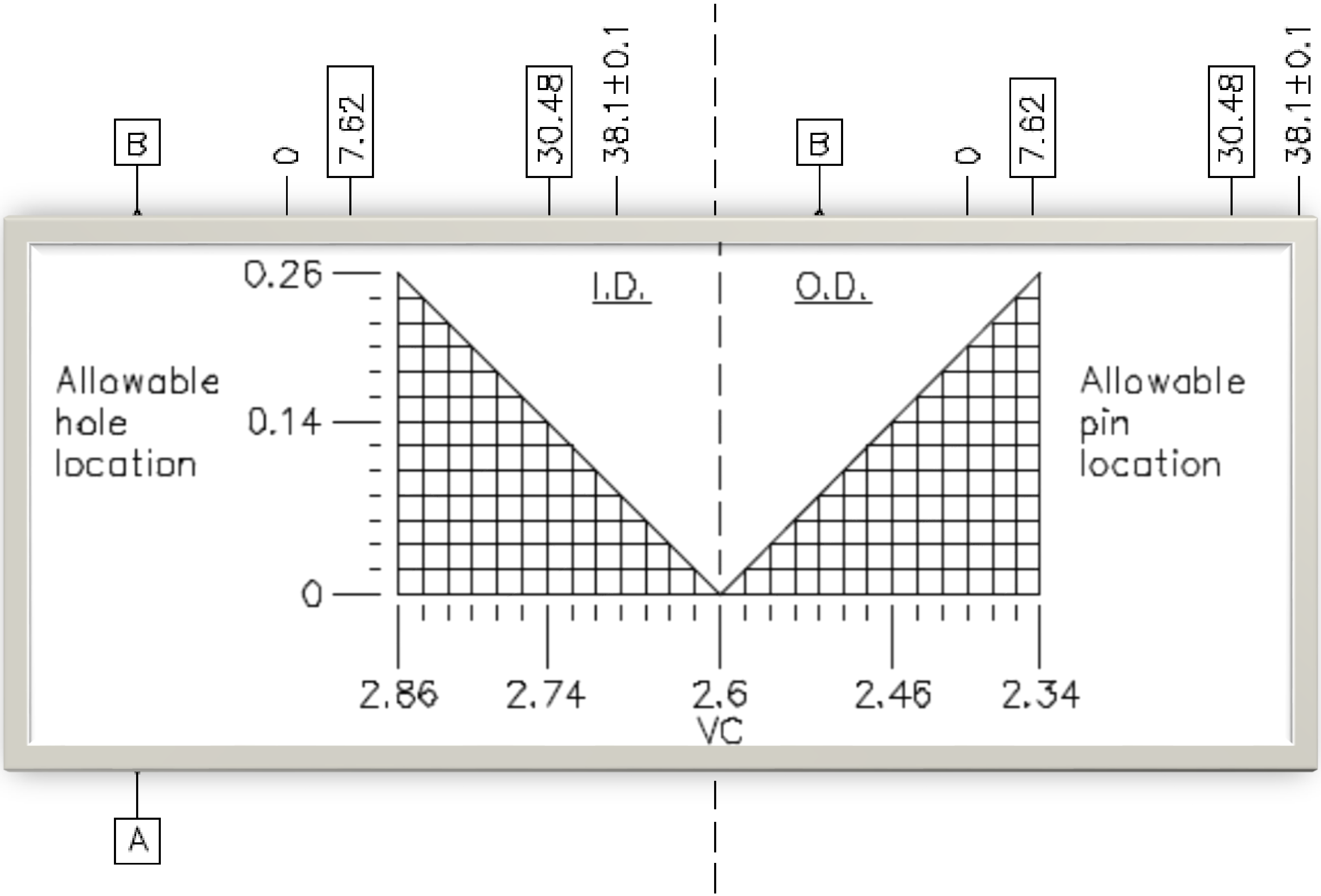
4 Pin Example



4 Pin Example



4 Pin Example



4 Pin Example Summary