Introduction to Tolerancing and Dimensioning

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

Collected by A. Trimble
Additional Slides Added by M. Nejhad & T. Sorensen
Dimensioning
Solid Model to Technical Drawing
6 Views with Dimensioning
Tolerancing
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 (American National Standard Institute)
      - ISO (International Organization for Standardization)
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
### Process Driven

- **Tolerance Grades**

<table>
<thead>
<tr>
<th>IT Grade</th>
<th>Measuring Tools</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01 01 01 01 01 01 01 01 01 01 01 01 01 01</td>
<td>Fits</td>
</tr>
</tbody>
</table>

![Table 7: Relation of Machining Processes to Tolerance Grades (ANSI B4, 1-1967 (R2009))](image)

*This chart may be used as a general guide to determine the machining processes that will yield normal conditions, produce work within the tolerance grades indicated. (See also Relation of Surface Roughness to Tolerances starting on page 738.)*
Process Driven
Process Driven

<table>
<thead>
<tr>
<th>Tolerance Level</th>
<th>Diameter Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0005 in. (0.013 mm)</td>
<td>0.001 in. (0.025 mm)</td>
</tr>
<tr>
<td>Tuning, boring</td>
<td>Diameter &lt; 1.0 in.</td>
</tr>
<tr>
<td>Drilling</td>
<td>Diameter &lt; 0.1 in.</td>
</tr>
<tr>
<td>Reaming</td>
<td>Diameter &lt; 0.5 in.</td>
</tr>
<tr>
<td>Milling</td>
<td>Peripheral</td>
</tr>
<tr>
<td>Shaping, slotting</td>
<td></td>
</tr>
<tr>
<td>Planing</td>
<td></td>
</tr>
<tr>
<td>Broaching</td>
<td></td>
</tr>
<tr>
<td>Sawing</td>
<td></td>
</tr>
</tbody>
</table>

*Drilling tolerances typically expressed as a biased bilateral tolerance (for example, +0.005/-0.003). Values in this tabulation are expressed as closest bilateral tolerance (e.g., ±0.003).
Surface Deviations

Form, Waviness, Roughness

Waviness profile (red)

Long cutoff = “smooth” waviness
“higher” roughness

Roughness profile (blue)

Short cutoff = “bumpy” waviness
“smoother” roughness

Waviness Profile

Roughness Profile
Process Driven
Indicative surface roughness comparisons

<table>
<thead>
<tr>
<th>Roughness Grade Numbers (New)**</th>
<th>Roughness Grade Numbers (Old)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_a micrometer µm</td>
<td>R_a micro-inch µ in</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>50</td>
<td>2000</td>
</tr>
<tr>
<td>25</td>
<td>1000</td>
</tr>
<tr>
<td>12.5</td>
<td>500</td>
</tr>
<tr>
<td>6.3</td>
<td>250</td>
</tr>
<tr>
<td>3.2</td>
<td>125</td>
</tr>
<tr>
<td>1.6</td>
<td>63</td>
</tr>
<tr>
<td>0.8</td>
<td>32</td>
</tr>
<tr>
<td>0.4</td>
<td>16</td>
</tr>
<tr>
<td>0.2</td>
<td>8</td>
</tr>
<tr>
<td>0.1</td>
<td>4</td>
</tr>
<tr>
<td>0.05</td>
<td>2</td>
</tr>
<tr>
<td>0.025</td>
<td>1</td>
</tr>
</tbody>
</table>

R_a Range

<table>
<thead>
<tr>
<th>R_t</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_a)</td>
<td>6.3</td>
</tr>
<tr>
<td>Old Style</td>
<td>250</td>
</tr>
<tr>
<td>American standard</td>
<td>250</td>
</tr>
</tbody>
</table>

Roughness Grade Numbers and Ra Measures...

REMOVAL OF MATERIAL

SURFACE MAY BE PRODUCED BY ANY METHOD
MATERIAL REMOVAL REQUIRED
MATERIAL REMOVAL PROHIBITED

X = LETTER HEIGHT

A Trimble, M. Nejhad, & T. Sorensen
ME 482 – Spring 2024
# Surface Finish

![Surface Finish Diagram](image)

<table>
<thead>
<tr>
<th>Basic Surface Texture Symbol</th>
<th>Maximum Waviness Spacing Rating (C). Specify in inches or millimeters. Horizontal bar added to basic symbol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROUGHNESS AVERAGE VALUES (A). Specify in microinches, micrometers, or roughness grade numbers.</td>
<td>LAY SYMBOL (E)</td>
</tr>
<tr>
<td>MAXIMUM AND MINIMUM ROUGHNESS AVERAGE VALUES (A), SPECIFY IN MICROINCHES, MICROMETERS, OR ROUGHNESS GRADE NUMBERS.</td>
<td>ROUGHNESS SAMPLING LENGTH OR CUTOFF RATING (D). WHEN NO VALUE IS SHOWN USE .03 INCH (0.8 MILLIMETERS).</td>
</tr>
<tr>
<td>MAXIMUM WAVINESS HEIGHT RATING (B) SPECIFY IN INCHES OR MILLIMETERS. HORIZONTAL BAR ADDED TO BASIC SYMBOL.</td>
<td>MACHINING ALLOWANCE (F). SPECIFY IN INCHES OR MILLIMETERS.</td>
</tr>
</tbody>
</table>

**NOTE:** WAVINESS IS NOT USED IN ISO STANDARDS.
# Surface Finish

<table>
<thead>
<tr>
<th>Lay Symbol</th>
<th>Meaning</th>
<th>Example Showing Direction of Tool Marks</th>
</tr>
</thead>
<tbody>
<tr>
<td>=</td>
<td>Lay approximately parallel to the line representing the surface to which the symbol is applied.</td>
<td>![Example]</td>
</tr>
<tr>
<td>⊥</td>
<td>Lay approximately perpendicular to the line representing the surface to which the symbol is applied.</td>
<td>![Example]</td>
</tr>
<tr>
<td>X</td>
<td>Lay angular in both directions to line representing the surface to which the symbol is applied.</td>
<td>![Example]</td>
</tr>
<tr>
<td>M</td>
<td>Lay multidirectional.</td>
<td>![Example]</td>
</tr>
<tr>
<td>C</td>
<td>Lay approximately circular relative to the center of the surface to which the symbol is applied.</td>
<td>![Example]</td>
</tr>
<tr>
<td>R</td>
<td>Lay approximately radial relative to the center of the surface to which the symbol is applied.</td>
<td>![Example]</td>
</tr>
<tr>
<td>P^3</td>
<td>Lay particular, multi-directional, or protruberant.</td>
<td>![Example]</td>
</tr>
</tbody>
</table>
## Surface Finish

<table>
<thead>
<tr>
<th>Micrometers Rating</th>
<th>Microinches Rating</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1000</td>
<td>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.</td>
</tr>
<tr>
<td>12.5</td>
<td>500</td>
<td>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.</td>
</tr>
<tr>
<td>6.3</td>
<td>250</td>
<td>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.</td>
</tr>
<tr>
<td>3.2</td>
<td>125</td>
<td>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.</td>
</tr>
<tr>
<td>1.6</td>
<td>63</td>
<td>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.</td>
</tr>
<tr>
<td>0.8</td>
<td>32</td>
<td>A high-grade machine finish requiring close control when produced by lathes, shapers, milling machines, etc., but relatively easy to produce 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.</td>
</tr>
<tr>
<td>0.4</td>
<td>16</td>
<td>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.</td>
</tr>
<tr>
<td>0.2</td>
<td>8</td>
<td>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.</td>
</tr>
<tr>
<td>0.1</td>
<td>4</td>
<td>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.</td>
</tr>
<tr>
<td>0.05</td>
<td>2</td>
<td>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.</td>
</tr>
<tr>
<td>0.025</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

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A Trimble, M. Nejhad, & T. Sorensen

ME 482 – Spring 2024
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

<table>
<thead>
<tr>
<th>Decimal Places</th>
<th>Notation</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X.X</td>
<td>± 0.2”</td>
</tr>
<tr>
<td>2</td>
<td>X.XX</td>
<td>± 0.01”</td>
</tr>
<tr>
<td>3</td>
<td>X.XXX</td>
<td>± 0.005”</td>
</tr>
<tr>
<td>4</td>
<td>X.XXXXX</td>
<td>± 0.0005”</td>
</tr>
</tbody>
</table>

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
Tolerances/Surface Finish & Costs

Approximate Relative Cost of Progressively Tighter Dimensional Tolerances

- Rough machining, +/- 0.030: 101
- Standard machining, +/- 0.005: 200
- Fine machining, +/- 0.001: 440
- Very fine machining, +/- 0.0005: 720
- Fine grinding, +/- 0.0002: 1400
- Very fine grinding, +/- 0.0001: 2400
- Lapping, polishing, +/- 0.00005: 4500

N.E. Woldman, Machinability and Machining of Metals

Surface Finish →

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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 (DFQ)

**DFQ**: Design For Quality

**DFM**: Design For Manufacturing

**DFMEA**: Design of Failure Mode & Effect Analysis
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

![Diagram of normal distribution with specification limits](image)

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: $C_p = \frac{8\sigma}{6\sigma} = \frac{4}{3} = 1.33$

Ford motor company 305 BOSS:
Rod and main bores manufacturing tolerances $\pm 0.003"$.

- Crankshaft
  - Diameter $\approx 2" \pm 0.0003"
  - $\Rightarrow$ Process Capability $= \pm 0.0003"$
$C_p \equiv$ Capability index or Concurrent Engineering Index: Design / Manufacturing

\[
-C_p = \frac{Spec \ Limits}{Process \ Capability} = \frac{USL-LSL}{\pm \sigma}
\]

- Automotive: $C_p = 1.33$

![Diagram showing $C_p$ value and process capability](image)
Cpk

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

\[
C_p = \frac{12\sigma}{6\sigma} = 2
\]
\[
K = \frac{1.5\sigma}{6\sigma} = 0.25
\]
Some Statistical Quality measures

- $C_p = \frac{U-L}{6\sigma}$, measure of the spread of the population about the average
- $C_{pk} = \min(C_{pl}, C_{pu})$, 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

<table>
<thead>
<tr>
<th>Sigma</th>
<th>Defects per Million</th>
<th>Cost of Poor Quality</th>
<th>Quality Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Sigma</td>
<td>3.4</td>
<td>&lt;10% of sales</td>
<td>World Class</td>
</tr>
<tr>
<td>5 Sigma</td>
<td>233</td>
<td>10-15% of sales</td>
<td></td>
</tr>
<tr>
<td>4 Sigma</td>
<td>6210</td>
<td>15-20% of sales</td>
<td>Industry Average</td>
</tr>
<tr>
<td>3 Sigma</td>
<td>66,807</td>
<td>20-30% of sales</td>
<td></td>
</tr>
<tr>
<td>2 Sigma</td>
<td>308,537</td>
<td>30-40% of sales</td>
<td>Noncompetitive</td>
</tr>
<tr>
<td>1 Sigma</td>
<td>690,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fits

Allowance always equals smallest hole minus largest shaft
Fits General

(A) Hole 40 H8
- Basic size
- Fundamental deviation
- Tolerance grade
- IT grade

(B) Shaft 40 f7
- Basic size
- Fundamental deviation
- Tolerance grade
- IT grade

(C) Fit 40 H8/f7
- Hole tolerance
- Shaft tolerance
- Tolerance grade
Fits Shaft Driven (Shaft basis System)
Fits Hole Driven

- Hole basis system: fits

- Clearance
- Transition
- Interference

- Hole tolerance
- Minimum clearance
- Maximum clearance
- Shaft tolerance
- Minimum interference
- Maximum interference
- Basic size
## Fits ANSI

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

<table>
<thead>
<tr>
<th>Nominal Size Range, Inches</th>
<th>Class RC 1</th>
<th>Class RC 2</th>
<th>Class RC 3</th>
<th>Class RC 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clearance&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Clearance&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Clearance&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Clearance&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Hole H5</td>
<td>Shaft g4</td>
<td>Hole H6</td>
<td>Shaft g5</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>0 - 0.12</td>
<td>0.1</td>
<td>+0.2</td>
<td>-0.1</td>
<td>+0.25</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0</td>
<td>-0.25</td>
<td>0.55</td>
</tr>
<tr>
<td>0.12 - 0.24</td>
<td>0.15</td>
<td>+0.2</td>
<td>-0.15</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0</td>
<td>-0.3</td>
<td>0.65</td>
</tr>
<tr>
<td>0.24 - 0.40</td>
<td>0.2</td>
<td>+0.25</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0</td>
<td>-0.35</td>
<td>0.85</td>
</tr>
<tr>
<td>0.40 - 0.71</td>
<td>0.25</td>
<td>+0.3</td>
<td>-0.25</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0</td>
<td>-0.45</td>
<td>0.95</td>
</tr>
<tr>
<td>0.71 - 1.19</td>
<td>0.3</td>
<td>+0.4</td>
<td>-0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>0</td>
<td>-0.55</td>
<td>1.2</td>
</tr>
<tr>
<td>1.19 - 1.97</td>
<td>0.4</td>
<td>+0.4</td>
<td>-0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>-0.7</td>
<td>1.4</td>
</tr>
<tr>
<td>1.97 - 3.15</td>
<td>0.4</td>
<td>+0.5</td>
<td>-0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>0</td>
<td>-0.7</td>
<td>1.6</td>
</tr>
<tr>
<td>3.15 - 4.73</td>
<td>0.5</td>
<td>+0.6</td>
<td>-0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>0</td>
<td>-0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>4.73 - 7.09</td>
<td>0.6</td>
<td>+0.7</td>
<td>-0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>0</td>
<td>-1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>7.09 - 9.85</td>
<td>0.6</td>
<td>+0.8</td>
<td>-0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0</td>
<td>-1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>9.85 - 12.41</td>
<td>0.8</td>
<td>+0.9</td>
<td>-0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>0</td>
<td>-1.4</td>
<td>2.9</td>
</tr>
<tr>
<td>12.41 - 15.75</td>
<td>1.0</td>
<td>+1.0</td>
<td>-1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>0</td>
<td>-1.7</td>
<td>3.4</td>
</tr>
<tr>
<td>15.75 - 19.69</td>
<td>1.2</td>
<td>+1.0</td>
<td>-1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>0</td>
<td>-2.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Values shown below are in thousands of an inch.
## Fits ISO

<table>
<thead>
<tr>
<th>ISO SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>H11/c11</td>
<td>Loose running fit for wide commercial tolerances or allowances on external members.</td>
</tr>
<tr>
<td>H9/d9</td>
<td>Free running fit not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures.</td>
</tr>
<tr>
<td>H8/f7</td>
<td>Close Running fit for running on accurate machines and for accurate moderate speeds and journal pressures.</td>
</tr>
<tr>
<td>H7/g6</td>
<td>Sliding fit not intended to run freely, but to move and turn freely and locate accurately.</td>
</tr>
<tr>
<td>H7/h6</td>
<td>Locational clearance fit provides snug fit for locating stationary parts; but can be freely assembled and disassembled.</td>
</tr>
<tr>
<td>H7/k6</td>
<td>Locational transition fit for accurate location, a compromise between clearance and interference.</td>
</tr>
<tr>
<td>H7/m6</td>
<td>Locational transition fit for more accurate location where greater interference is permissible.</td>
</tr>
<tr>
<td>H7/p6</td>
<td>Locational interference fit for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements.</td>
</tr>
<tr>
<td>H7/s6</td>
<td>Medium drive fit for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron.</td>
</tr>
<tr>
<td>H7/u6</td>
<td>Force fit suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical.</td>
</tr>
</tbody>
</table>

*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

Ø 0.03

A B C
Definitions

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

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

Engineering Dimensioned Drawing

Upper Limit (MMC)

Lower Limit (LMC)

Upper Limit (LMC)

Lower Limit (MMC)
Definitions

• Regardless of Feature Size (RFS) $s$
  
  – Tolerances apply to a geometric feature regardless of its size. These sizes range from MMC to LMC.
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

3.175
6.375-3.175=3.2
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
Theory Vs Reality

Axis

Plane

Datum Feature ‘A’ (Surface)
Datum ‘A’ (Theoretical Plane)
Datums and Design Intent
Datum Choices

![Diagram of Datum Choices]
As built
Datum Intent
### Some Controls

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Type of Feature Controlled</th>
<th>Feature Control Options</th>
<th>Feature Control Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straightness</td>
<td></td>
<td>CYL-SURFACE ELEMENTS</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CYL-DETECTED MEDIAN LINE</td>
<td>a, d</td>
<td>∅</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLANE-LINE ELEMENTS</td>
<td>b, c</td>
<td>0</td>
</tr>
<tr>
<td>Flatness</td>
<td>□</td>
<td>PLANE</td>
<td>b, c</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WIDTH-DETECTED MEDIAN PLANE</td>
<td>a, d</td>
<td>√</td>
</tr>
<tr>
<td>Circularity</td>
<td>□</td>
<td>REVOLUTE, SPHERE</td>
<td>a, b, d</td>
<td>0</td>
</tr>
<tr>
<td>Cylindricity</td>
<td></td>
<td>CYLINDER</td>
<td>a, b, d</td>
<td>0</td>
</tr>
<tr>
<td>Profile of a line</td>
<td></td>
<td>ALL</td>
<td>b</td>
<td>0-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>REVOLUTE</td>
<td>b</td>
<td>0-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OTHER (NON-REVOLUTE)</td>
<td>b</td>
<td>0-3</td>
</tr>
<tr>
<td>Profile of a surface</td>
<td></td>
<td>COPLANARITY OF PLANES</td>
<td>b</td>
<td>0</td>
</tr>
<tr>
<td>Perpendicularity</td>
<td></td>
<td>PLANE (INCLINE ELEMENTS)</td>
<td>b, c</td>
<td>1-3</td>
</tr>
<tr>
<td>Parallelism</td>
<td></td>
<td>CYLINDER</td>
<td>a, d</td>
<td>∅</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WIDTH</td>
<td>a, d</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td>REVOLUTE-RADIAL ELEMENT</td>
<td>b, c</td>
<td>1-3</td>
</tr>
<tr>
<td>Angularity</td>
<td></td>
<td>PLANE (INCLINE ELEMENTS)</td>
<td>b, c</td>
<td>1-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CYLINDER</td>
<td>a, d</td>
<td>∅</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WIDTH</td>
<td>a, d</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td>REVOLUTE-RADIAL ELEMENT</td>
<td>b, c</td>
<td>1-3</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td>CYLINDER</td>
<td>a, d</td>
<td>∅</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WIDTH</td>
<td>a, d</td>
<td>√</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPHERE</td>
<td>c, d</td>
<td>∅</td>
</tr>
<tr>
<td>Concentricity</td>
<td></td>
<td>ALL NON-SPHERICAL</td>
<td>a, b, d</td>
<td>∅</td>
</tr>
<tr>
<td>Symmetry</td>
<td></td>
<td>SPHERE</td>
<td>a, b, d</td>
<td>∅</td>
</tr>
<tr>
<td>Circular Runout</td>
<td></td>
<td>OPPOSED POINTS</td>
<td>a, d</td>
<td>1-3</td>
</tr>
<tr>
<td>Total Runout</td>
<td></td>
<td>REVOLUTE</td>
<td>a, b, d</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CYLINDER</td>
<td>a, b, d</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLANE PERP TO AXIS</td>
<td>b, c</td>
<td>1-2</td>
</tr>
</tbody>
</table>
Flatness
Circularity

[Diagram showing a part with dimensions and tolerances indicated by annotations like \( \phi.73 \pm 0.005 \), \( \phi.72 \), \( \phi.73 \pm 0.005 \), \( \phi.782 \), and \( \phi.772 \).]
GD&T

[Diagram showing GD&T symbol with dimensions and tolerance notes]
Tolerance Zone
Location

- **4 Pins & 4 Holes**
  
  - Pins: $2.4 \pm 0.06 = 2.46 \text{ & } 2.34 \ (\Delta = 0.12)$
  
  - Holes: $2.8 \pm 0.06 = 2.86 \text{ & } 2.74 \ (\Delta = 0.12)$

- Square Size = 0.05 $\Rightarrow$ Dia = 0.07070 ($x2 = 0.14$)

- $0.14 + 0.12 = 0.26$
Location
4 Pin Example
4 Pin Example
Tolerance Zone

\[ \Phi 0.1414 \text{ zone} \]

\[ 0.0707 R \]
\[ \text{(hypotenuse)} \]

\[ 0.05 \text{ (X and Y)} \]
4 Pin Example
4 Pin Example

Allowable hole location

Allowable pin location

I.D.  O.D.

2.86  2.74  2.6 VC  2.46  2.34

0.26  0.14  0
4 Pin Example

Diagram showing dimensions and tolerances for a 4-pin example, including symbols and measurements.
4 Pin Example
4 Pin Example
4 Pin Example Summary
4 Pin Example
Summary & Recap of Tolerancing (GD&T)

Summary & Recap of Tolerancing

Figure 21.21 Types of fits: (A) clearance fit, (B) transition fit, where there can be either interference or clearance, and (C) interference fit, where the parts must be forced together.

Figure 21.23 This diagram illustrates the preferred fits for a shaft-basis system listed in Fig. 21.20. Appendixes 42 and 43 give values for these fits.

clearance fit of C11/h11 to an interference fit of U7/h6 (see Fig. 21.20).

Standard Cylindrical Fits
The following examples demonstrate how to calculate and apply tolerances to cylindrical parts. The solutions involve the use of Appendix 40, Fig. 21.18, and Fig. 21.20.

Example 1 (Fig. 21.24)

Required: Use the hole-basis system, a close-running fit, and a basic diameter of 49 mm.

Solution: Use a preferred basic diameter of 50 mm (Fig. 21.18) and fit of H8/f7 (Fig. 21.20).

Hole: Find the upper and lower limits of the hole in Appendix 40 under H8 and across from 50 mm. These limits are 50.000 and 50.039 mm.
Summary & Recap of Tolerancing (GD&T)
Summary & Recap of Tolerancing

**Table of Angular Tolerances**

<table>
<thead>
<tr>
<th>Length of Shorter Leg (mm)</th>
<th>Up To 10</th>
<th>Over 10 To 50</th>
<th>Over 50 To 120</th>
<th>Over 120 To 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance</td>
<td>±1°</td>
<td>±0°30'</td>
<td>±0°20'</td>
<td>±0°10'</td>
</tr>
</tbody>
</table>

*Values in degrees and minutes taken from previous table.*

**Geometric Symbols**

**Tolerance**

- Straightness
- Flatness
- Circularity
- Cylindricity

**Form**

**Profile**

- Profile of a Line
- Profile of a Surface

**Orientation**

- Angularity
- Perpendicularity
- Parallelism

**Location**

- Position
- Concentricity

**Runout**

- Circular Runout
- Total Runout

**Proportions of Symbols**

- Datum Basic Dim Feature Control Target Pt
- Frame Height
- Concentricity
- Circularity
- MMC
- LMC
- RFS
- Proj TOL
- Parallelism
- Flatness
- Cylindricity
- DIA
- Position
- All Around Profile
- Profile Surface
- Profile Line
- Straightness

*Figure 21.38* Extracted from Fig. 21.37, this table of values inserted on a drawing would indicate general tolerances for angles in degrees and minutes.

*Figure 21.40* Use these general proportions (based on the letter height used) for drawing feature control symbols and frames.

**21.13 Geometric Tolerances**

Geometric tolerancing specifies tolerances that control location form, profile, orientation, and runout on a dimensioned part as covered by the ANSI Y14.5M-1982 Standards and the Military Standards (Mil-Std) of the U.S. Department of Defense. Before discussing those types of tolerancing, however, we need to introduce you to some general limits. Along with these datum planes...
Summary & Recap of Tolerancing

**Square vs. Circular Tolerance Zones**

- **Figure 21.53**
  A. These dimensions give a square tolerance zone for the axis of the hole.
  B. Basic dimensions (in frames) locate the true center about which a circular tolerance zone of 0.8 mm is specified.

- **Figure 21.54**
  The square method of tolerancing gives a square tolerance zone with a diagonal that exceeds the specified tolerance by a factor of 1.4.

- **Figure 21.55**
  The true-position method of tolerancing gives a circular tolerance zone with its center at the true position of the hole. The circular tolerance zone can be 1.4 times greater than the square tolerance zone and still be as accurate.

The circular tolerance zone specified in the circular view of a hole extends the full depth of the hole. **Therefore the tolerance zone for the centerline of the hole is a cylindrical zone inside which the axis must lie.** Because both the size of the hole and its position are tolerated, these two tolerances establish the diameter of a gauge cylinder for checking conformance of hole sizes and their locations against specifications (Fig. 21.56).

Subtracting the true-position tolerance from the hole at MMC (the smallest permissible hole) yields the circle that represents the least favorable condition when the part is gauged or assembled with a mating part. When the hole is not at MMC, the tolerance zone size is the tolerance and axis.
Summary & Recap of Tolerancing

**Figure 21.59** Concentricity is a tolerance of location. Here, the feature control frame specifies that the axis of the small cylinder be concentric to datum cylinder A, within a tolerance of 0.3 mm diameter.

**Figure 21.61** Symmetry is a tolerance of location. It specifies that a part’s features be symmetrical about the center plane between parallel surfaces of the part.

**Figure 21.60** This typical feature control frame indicates that a surface is concentric to datum C within a cylindrical diameter of 0.4 mm at MMC.

**Figure 21.62** Flatness is a tolerance of form. It specifies a tolerance zone within which an object’s surface must lie.
Summary & Recap of Tolerancing

**Figure 21.63** Straightness is a tolerance of form. It indicates that elements of a surface are straight lines. The tolerance frame is applied to the views in which elements appear as straight lines.

**Figure 21.64** Roundness is a tolerance of form. It indicates that a cross section through a surface of revolution is round and lies within two concentric circles.

**Figure 21.65** Roundness of a sphere means that any cross section through it is round within the specified tolerance.

**Figure 21.66** Cylindricity is a tolerance of form that is a combination of roundness and straightness. It indicates that the surface of a cylinder lies within a tolerance zone formed by two concentric cylinders.

mm on the radius. **Figure 21.65** specifies a 0.30 mm tolerance zone for the roundness of a sphere.
Summary & Recap of Tolerancing

**Figure 21.67** Profile is a tolerance of form for irregular curves of planes. (A) The curving plane is located by coordinates and is tolerated unidirectionally. (B) The tolerance may be applied by any of these methods.

**Figure 21.68** The profile of a line is a tolerance of form that specifies the variation allowed from the path of a line. Here, the line is formed by tangent arcs. The tolerance zone may be either bilateral or unilateral, as shown in Fig. 21.70.

**Figure 21.69** Parallelism is a tolerance of form. It indicates that a plane is parallel to a datum plane within specified limits. Here, plane B is the datum plane.

Tangent arcs whose radii are given as basic dimensions. The radii are permitted to vary ±0.10 mm from the basic radii.

21.19 **Orientation Tolerancing**

Tolerances of orientation include parallelism, perpendicularity, and angularity.

**Parallelism** A surface or line is parallel when all its points are equidistant from a datum plane or axis. Two types of parallelism tolerance zones are:

1. A planar tolerance zone parallel to a datum plane within which the axis or surface of the feature must lie (Fig. 21.69). This tolerance also controls flatness.

2. A cylindrical tolerance zone parallel to a datum feature within which the axis of a feature must lie (Fig. 21.70).
Summary & Recap of Tolerancing

**Figure 21.70** You may specify parallelism of one centerline to another by using the diameter of one of the holes as the datum.

**Figure 21.71** The critical tolerance exists when features are at MMC. (A) The upper hole must be parallel to the hole used as datum A within a 0.20 DIA. (B) As the hole approaches its maximum size of 30.30 mm, the tolerance zone approaches 0.50 mm.

**Figure 21.72** Perpendicularity is a tolerance form that gives a tolerance zone for a plane perpendicular to a specified datum plane.

**Figure 21.73** Perpendicularity can apply to the axis of a feature, such as the centerline of a cylinder.

**Angularity** A surface or line is angular when it is not parallel to a datum feature.
Summary & Recap of Tolerancing

Figure 21.74 Angularity is a tolerance of form specifying the tolerance zone for an angular surface with respect to a datum plane. Here, the 30° angle is a true, or basic, angle to which a tolerance of 0.25 mm is applied.

Figure 21.75 Runout tolerance, a composite of several tolerances of form characteristics, is used to specify concentric cylindrical parts. The part is mounted on the datum axis and is gauged as it is rotated.

Figure 21.76 Here, runout tolerance is measured by mounting the object on the primary datum plane C and the secondary datum cylinder D. The cylinder and conical surface are gauged to check their conformity to a tolerance zone of 0.03 mm. The runout at the end of the cone could have been noted.

Frame indicates circular runout; two arrows indicate total runout.

Circular Runout Rotating an object about its axis 360° determines whether a circular cross section exceeds the permissible runout tolerance at any point (Fig. 21.76). This same technique is used to measure the amount of wobble in surfaces perpendicular to the axis of rotation.

Total Runout Used to specify cumulative varia-
Summary & Recap of Tolerancing

Figure 21.78 These are the definitions of surface texture for a finished surface.

Surface Texture

The texture of a part affects its quality and performance, and it is usually specified instead of geometric features. A part of the part that you can see is called the texture of the texture of the part. The surface texture affects the part's quality, performance, and ability to interact with other parts. The surface texture is specified using symbols and notes, such as standard symbols for surface finish, waviness, lay, and flaws. The surface texture is specified using symbols and notes, such as standard symbols for surface finish, waviness, lay, and flaws.

Surface Texture Symbols

- A. Basic Surface Texture Symbol: Surface may be produced by any method.
- B. Material Removal by Machining: Indicated by horizontal bar.
- C. Material Removal Allowance: The amount of stock (mm or in.) to be removed by machining.
- D. Material Removal Prohibited: Surface to be produced by hot finishing, casting, die casting, etc. without removing material.
- E. Surface Texture Symbol: Used when values for surface characteristics are added above the horizontal or to the right of the line.
- F. Machining Symbols: The symbols below are used to recommend machining operations.

Figure 21.79 Use surface texture symbols to specify surface finish on the edge views of finished surfaces.

Waviness: A widely spaced variation that exceeds the roughness, but is defined in micrometers.
Summary & Recap of Tolerancing

Figure 21.80 Values may be added to surface control symbols for more precise specifications.

regarded as a surface variation superimposed on a wavy surface.

Waviness height: the peak-to-valley distance between waves measured in inches or millimeters.

Waviness width: the spacing between wave peaks or valleys at right angles to the lay symbol.

Figure 21.79 shows symbols for specifying surface texture. The point of the must touch the edge view of the surface, an extension line from the surface, or a leader pointing to the surface.

Figure 21.81 Various types of production methods result in the surface roughness heights shown in micrometers and micrometers (milli-inches of a meter or an inch).

A Trimble, M. Nejhad, & T. Sorensen