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

Colt Peace Maker

Early 1900’s assembly line

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
### Process Driven

- **Tolerance Grades**

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

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

This chart may be used as a general guide to determine the machining processes that will under 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

![Diagram showing tolerances for machining processes]

<table>
<thead>
<tr>
<th>Process</th>
<th>± Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuning, boring</td>
<td>±0.0005 in. (±0.013 mm)</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.001 in. (±0.0025 mm)</td>
</tr>
<tr>
<td></td>
<td>0.002 in. (±0.005 mm)</td>
</tr>
<tr>
<td></td>
<td>0.003 in. (±0.0075 mm)</td>
</tr>
<tr>
<td></td>
<td>0.005 in. (±0.0125 mm)</td>
</tr>
<tr>
<td></td>
<td>0.010 in. (±0.025 mm)</td>
</tr>
<tr>
<td></td>
<td>0.015 in. (±0.038 mm)</td>
</tr>
<tr>
<td></td>
<td>0.020 in. (±0.051 mm)</td>
</tr>
</tbody>
</table>

**Drilling**
- Diameter < 0.1 in.
- 0.5 in. ≤ Diameter ≤ 1.0 in.
- Diameter > 2.0 in.

**Raming**
- Diameter < 0.5 in.
- Diameter > 1.0 in.

**Milling**
- Peripheral
- Face
- End

**Shaping, slotting**

**Planing**

**Broaching**

**Sawing**

*Drilling tolerances typically expressed as a biased bilateral tolerance (e.g., ±0.005/−0.001). Values in this table are expressed as closest bilateral tolerance (e.g., ±0.003).*
Surface Deviations

Form, Waviness, Roughness

![Graphs showing Waviness and Roughness profiles with Long and Short cutoffs.](image-url)
Process Driven
### Indicative surface roughness comparisons

<table>
<thead>
<tr>
<th>Ra μm</th>
<th>50</th>
<th>37.5</th>
<th>25</th>
<th>12.5</th>
<th>6.3</th>
<th>3.2</th>
<th>1.6</th>
<th>0.8</th>
<th>0.4</th>
<th>0.2</th>
<th>0.1</th>
<th>0.05</th>
<th>0.025</th>
<th>0.012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra μm (GSA)</td>
<td>2000</td>
<td>1500</td>
<td>1000</td>
<td>500</td>
<td>250</td>
<td>125</td>
<td>63</td>
<td>32</td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### TUBE FINISHING
- Hot Extruded
- Cold Drawn
- Smooth Bore
- Electropolished

#### METAL CUTTING
- Sawing
- Planing, shaping
- Drilling
- Milling
- Boring, turning
- Broaching
- Reaming

#### ABRASIVE
- Grinding
- Barrel finishing
- Honing
- Electro-polishing
- Electrolytic grinding
- Polishing
- Lapping
- Superfinishing

#### FORMING
- Hot rolling
- Forging
- Extruding
- Cold rolling, drawing
- Roller burnishing

#### OTHER
- Flame cutting
- Chemical milling
- Laser cutting
- EDM

### Roughness Grade Numbers and Ra Measures...
## Surface Finish

### Table: Surface Finish Symbols

<table>
<thead>
<tr>
<th>Symbol Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Surface Texture Symbol</td>
<td><img src="example1.png" alt="Image" /></td>
</tr>
<tr>
<td>Maximum Waviness Spacing Rating (C). Specify in inches or millimeters. Horizontal bar added to basic symbol.</td>
<td><img src="example2.png" alt="Image" /></td>
</tr>
<tr>
<td>Roughness Average Values (A). Specify in microinches, micrometers, or roughness grade numbers.</td>
<td>63 N7 <img src="example3.png" alt="Image" /></td>
</tr>
<tr>
<td>Lay Symbol (E)</td>
<td><img src="example4.png" alt="Image" /></td>
</tr>
<tr>
<td>Maximum and Minimum Roughness Average Values (A). Specify in microinches, micrometers, or roughness grade numbers.</td>
<td>63 N7 32 N6 <img src="example5.png" alt="Image" /></td>
</tr>
<tr>
<td>Roughness Sampling Length or Cutoff Rating (D). When no value is shown use 0.03 inch (0.8 millimeters).</td>
<td><img src="example6.png" alt="Image" /></td>
</tr>
<tr>
<td>Maximum Waviness Height Rating (B). Specify in inches or millimeters. Horizontal bar added to basic symbol.</td>
<td>0.002 <img src="example7.png" alt="Image" /></td>
</tr>
<tr>
<td>Machining Allowance (F). Specify in inches or millimeters.</td>
<td>0.06 <img src="example8.png" alt="Image" /></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></td>
</tr>
<tr>
<td>⊥</td>
<td>Lay approximately perpendicular to the line representing the surface to which the symbol is applied.</td>
<td></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></td>
</tr>
<tr>
<td>M</td>
<td>Lay multidirectional.</td>
<td></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></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></td>
</tr>
<tr>
<td>P³</td>
<td>Lay particular, multidirectional, or protruberant.</td>
<td></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>1.8</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 cutters. It may be specified for close fits and used for all stressed parts, except fast rotating shafts, axes, 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 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.</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, gage 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>

A Trimble, M. Nejhad, & T. Sorensen.
# Surface Finish

## Roughness Scale

<table>
<thead>
<tr>
<th>Type</th>
<th>μm Ra</th>
<th>μ′ AA</th>
<th>μ″ AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>12.5</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Vertical</td>
<td>6.3</td>
<td>250</td>
<td>125</td>
</tr>
<tr>
<td>Turning</td>
<td>3.2</td>
<td>125</td>
<td>63</td>
</tr>
<tr>
<td>Turning</td>
<td>1.6</td>
<td>63</td>
<td>32</td>
</tr>
<tr>
<td>Turning</td>
<td>0.8</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>Turning</td>
<td>0.4</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Turning</td>
<td></td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

Average: 500

Compare by sight and feel (see GEJ-1136)
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>Tolerance Format</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 decimal place</td>
<td>X.X</td>
<td>± 0.2”</td>
</tr>
<tr>
<td>2 decimal places</td>
<td>X.XX</td>
<td>± 0.01”</td>
</tr>
<tr>
<td>3 decimal places</td>
<td>X.XXX</td>
<td>± 0.005”</td>
</tr>
<tr>
<td>4 decimal places</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
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%

Surface Finish →

N.E. Woldman, Machinability and Machining of Metals
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

Diagram showing the relationships between various design objectives and processes, including:
- Assembly Objectives
- Design for Assembly
- Datum Reference Frames
- Tolerance Analysis
- DG & T Drawing
- DFM
- KCs
- Tolerance Optimization
- COP/COPQ
- Design for Cost
- Design for Service
- Design for Transportation
- Performance Objectives
- Design for Life
- Design for Performance
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: $C_p = 1.33$

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

- Crankshaft
  - Diameter \(\approx 2" \pm 0.0003"\)
  - \(\Rightarrow Process \ Capability = 0.00025"\)
$C_p \equiv$ Capability index or Concurrent Engineering Index: Design / Manufacturing

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

- Automotive: $C_p = 1.33$
Cpk

- $C_{pk} \equiv \text{Process capability index adjusted for centering}$
- $C_{pk} = C_p (1 - k)$
  - $k \equiv \text{ratio of the amount the center has moved off target divided by the amount from the center to the nearest specification limit}$
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>
</tr>
</thead>
<tbody>
<tr>
<td>6 Sigma</td>
<td>3.4</td>
<td>&lt;10% of sales</td>
</tr>
<tr>
<td>5 Sigma</td>
<td>233</td>
<td>10-15% of sales</td>
</tr>
<tr>
<td>4 Sigma</td>
<td>6210</td>
<td>15-20% of sales</td>
</tr>
<tr>
<td>3 Sigma</td>
<td>66,807</td>
<td>20-30% of sales</td>
</tr>
<tr>
<td>2 Sigma</td>
<td>308,537</td>
<td>30-40% of sales</td>
</tr>
<tr>
<td>1 Sigma</td>
<td>690,000</td>
<td></td>
</tr>
</tbody>
</table>

World Class
Industry Average
Noncompetitive
Fits

Allowance always equals smallest hole minus largest shaft.

CLEARANCE FIT
Allowance = + .001

INTERFERENCE FIT
Allowance = - .003
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
Fits Shaft Driven (Shaft basis System)
Fits Hole Driven

- Hole basis system: fits
### 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*</td>
<td>Clearance*</td>
<td>Clearance*</td>
<td>Clearance*</td>
</tr>
<tr>
<td></td>
<td>Hole H5</td>
<td>Shaft g4</td>
<td>Hole H6</td>
<td>Shaft g5</td>
</tr>
<tr>
<td>0.01 - 0.12</td>
<td>0.1</td>
<td>+0.2</td>
<td>-0.1</td>
<td>+0.25</td>
</tr>
<tr>
<td>0.45</td>
<td>0</td>
<td>0</td>
<td>0.55</td>
<td>0</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>0.5</td>
<td>0</td>
<td>0</td>
<td>0.65</td>
<td>0</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>0.6</td>
<td>0</td>
<td>-0.35</td>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>0.71 - 1.19</td>
<td>0.25</td>
<td>+0.3</td>
<td>-0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>0.95</td>
<td>0.45</td>
<td>-0.5</td>
<td>0.95</td>
<td>0.5</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>1.1</td>
<td>0</td>
<td>0</td>
<td>1.2</td>
<td>0</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>1.2</td>
<td>0</td>
<td>-0.7</td>
<td>1.6</td>
<td>0</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>1.5</td>
<td>0</td>
<td>-0.9</td>
<td>2.0</td>
<td>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>1.8</td>
<td>0</td>
<td>-1.1</td>
<td>2.3</td>
<td>0</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>2.0</td>
<td>0</td>
<td>-1.2</td>
<td>2.6</td>
<td>0</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>2.3</td>
<td>0</td>
<td>-1.4</td>
<td>2.9</td>
<td>0</td>
</tr>
<tr>
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<td>-1.0</td>
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</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><strong>Loose running</strong> fit for wide commercial tolerances or allowances on external members.</td>
</tr>
<tr>
<td>H9/d9</td>
<td><strong>Free running</strong> 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><strong>Close Running</strong> fit for running on accurate machines and for accurate moderate speeds and journal pressures.</td>
</tr>
<tr>
<td>H7/g6</td>
<td><strong>Sliding fit</strong> not intended to run freely, but to move and turn freely and locate accurately.</td>
</tr>
<tr>
<td>H7/h6</td>
<td><strong>Locational clearance</strong> fit provides snug fit for locating stationary parts; but can be freely assembled and disassembled.</td>
</tr>
<tr>
<td>H7/k6</td>
<td><strong>Locational transition</strong> fit for accurate location, a compromise between clearance and interference.</td>
</tr>
<tr>
<td>H7/n6</td>
<td><strong>Locational transition</strong> fit for more accurate location where greater interference is permissible.</td>
</tr>
<tr>
<td>H7/p6</td>
<td><strong>Locational interference</strong> 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><strong>Medium drive</strong> 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><strong>Force</strong> 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
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

(b)

6.375

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

SECTION A-A
Theory Vs Reality

**Axis**

**Plane**

Datum Feature ‘A’ (Surface)

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

- Diagram 1: Datum A
- Diagram 2: Datum B
- Diagram 3: Datum B
As built
Datum Intent
### Some Controls

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Type of Feature Controlled</th>
<th>Feature Control Plane(s)</th>
<th>Feature Control Plane Options</th>
<th>Bounded by ( \pm ) ( \pm )</th>
<th>Boundary Layer ( \pm ) ( \pm )</th>
<th>Linear ( \pm ) ( \pm )</th>
<th>Angular ( \pm ) ( \pm )</th>
<th>Number of Data Allowed for ( \pm ) ( \pm )</th>
<th>Number of Datum Points Allowed for ( \pm ) ( \pm )</th>
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</table>
Flatness
Circularity

- Diameter: $\phi_{.75\pm.04}$
- Tolerance: $\pm .005$

- Part:
  - Spine for sweeping

- Tolerance zones:
  - Plane A-A: $\phi_{.73}$, $+ .005$
  - Plane B-B: $\phi_{.782}$, $- .005$
  - Shore: $\phi_{.772}$
Location

- **4 Pins & 4 Holes**

- Pines: $2.4 \pm 0.06 = 2.46 & 2.34 \ (\Delta = 0.12)$

- Holes: $2.8 \pm 0.06 = 2.86 & 2.74 \ (\Delta = 0.12)$

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

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

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

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

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

Allowable hole location

I.D.  O.D.

Allowable pin location

2.6

Let VC

2.86  2.74  2.6  2.46  2.34

0.26

0.14

0
4 Pin Example Summary
Summary & Recap of Tolerancing (GD&T)

Summary & Recap of Tolerancing

Types of Fit

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.

Preferred Fits: Shaft-Basis System

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.

Preferred Fits: Hole-Basis System

Figure 21.22: This diagram illustrates the preferred fits for the hole-basis system listed in Fig. 21.20. Appendixes 40 and 41 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 4 (Fig. 21.24)

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

Solution: Use a preferred basic diameter of 50 mm (Fig. 21.18) and fit of H8/I7 (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>
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<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.

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.

**Geometric Symbols**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straightness</td>
<td>—</td>
</tr>
<tr>
<td>Flatness</td>
<td>□</td>
</tr>
<tr>
<td>Circularity</td>
<td>○</td>
</tr>
<tr>
<td>Cylindricity</td>
<td>□</td>
</tr>
</tbody>
</table>

**Proportions of Symbols**

![Proportions of Symbols Image]

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 coordinate systems and three datum planes.
Summary & Recap of Tolerancing

**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.

**THE CIRCULAR TOLERANCE ZONE**

**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.

greater than the 0.1 tolerance permitted by the square zone, should be acceptable in the true-position tolerance method.

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, there is no way to establish the tolerance and axial...
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 21.60** 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 21.61** 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 21.62** 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.

**Cylindricity** A surface of revolution is cylindrical within 0.12 mm. On flat surfaces, straightness is
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 linear to datum plane C has a tolerance of 0.32 in. In Fig. 21.73 a hole is specified as perpendicular to datum plane A.
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 vari-
Summary & Recap of Tolerancing

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

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

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 limits.
Summary & Recap of Tolerancing

SURFACE TEXTURE

ROUGHNESS AVERAGE RATING (MAXIMUM) IN MICROINCHES OR MICROMETERS.

ROUGHNESS AVERAGE RATING (MAXIMUM AND MINIMUM) IN MICROINCHES OR MICROMETERS.

MAXIMUM WAVINESS HEIGHT (1ST NUMBER) IN MILLIMETERS OR INCHES, MAXIMUM WAVINESS HEIGHT RATING (2ND NUMBER) IN MILLIMETERS OR INCHES.

AMOUNT OF STOCK PROVIDED FOR MATERIAL REMOVAL IN MILLIMETERS OR INCHES.

REMOVAL OF MATERIAL IS PROHIBITED.

LAY DIRECTION IS PERPENDICULAR TO THIS EDGE OF THE SURFACE.

ROUGHNESS LENGTH OR CUTTOFF RATING IN MM OR INCHES BELOW THE HORIZONTAL WHEN NO VALUE IS SHOWN, USE 0.8mm (0.03 IN).

ROUGHNESS SPACING (MAXIMUM) IN MM OR INCHES IS PLACED TO THE RIGHT OF THE LAY SYMBOL.

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.