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Communicating Functional Requirements with GD&T

In The Beginning...

- Move from craft to industry
  - Emerging need for interchangeable parts
- Design and manufacturing close to each other
  - Easy communication
- Large dimensional tolerances
  - Compared to form capability
  - Form could be ignored when specifying and checking parts
- Tribal Knowledge
  - Many important requirements not documented

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Taylor

- Hard maximum material boundary
  - – Functionality deteriorates instantaneously
- Soft minimum material boundary
  - – Functionality deteriorates slowly

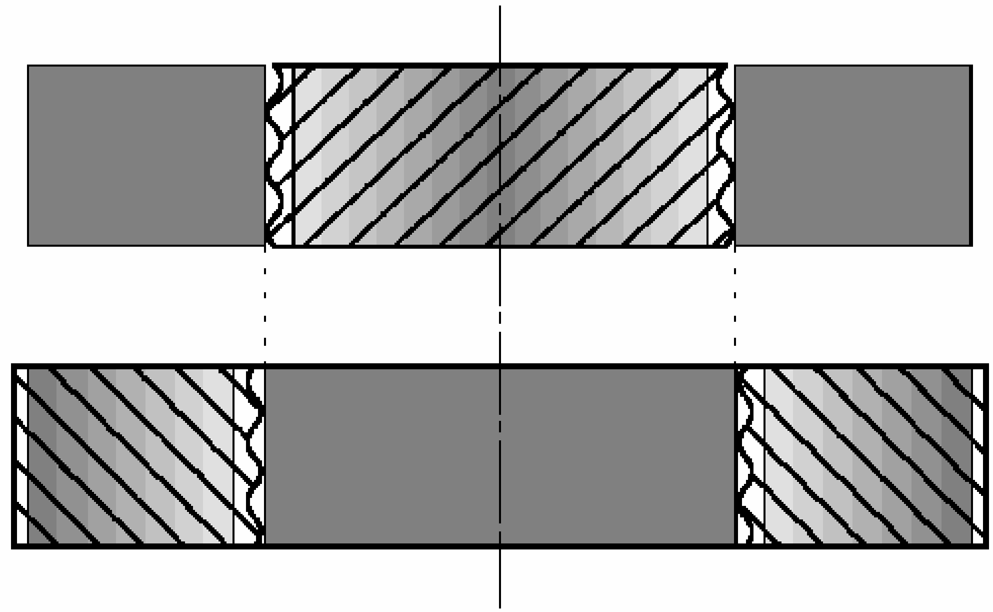

Figure 1: Static, Ridgid, Non-interference Fit Without Clearance. The shaft (top) has hard boundaries on the outside and "soft" boundaries on the inside. The hole (bottom) has hard boundaries on the inside and "soft" boundaries on the outside. The hard boundaries have the same diameter, i.e. the fit diameter.

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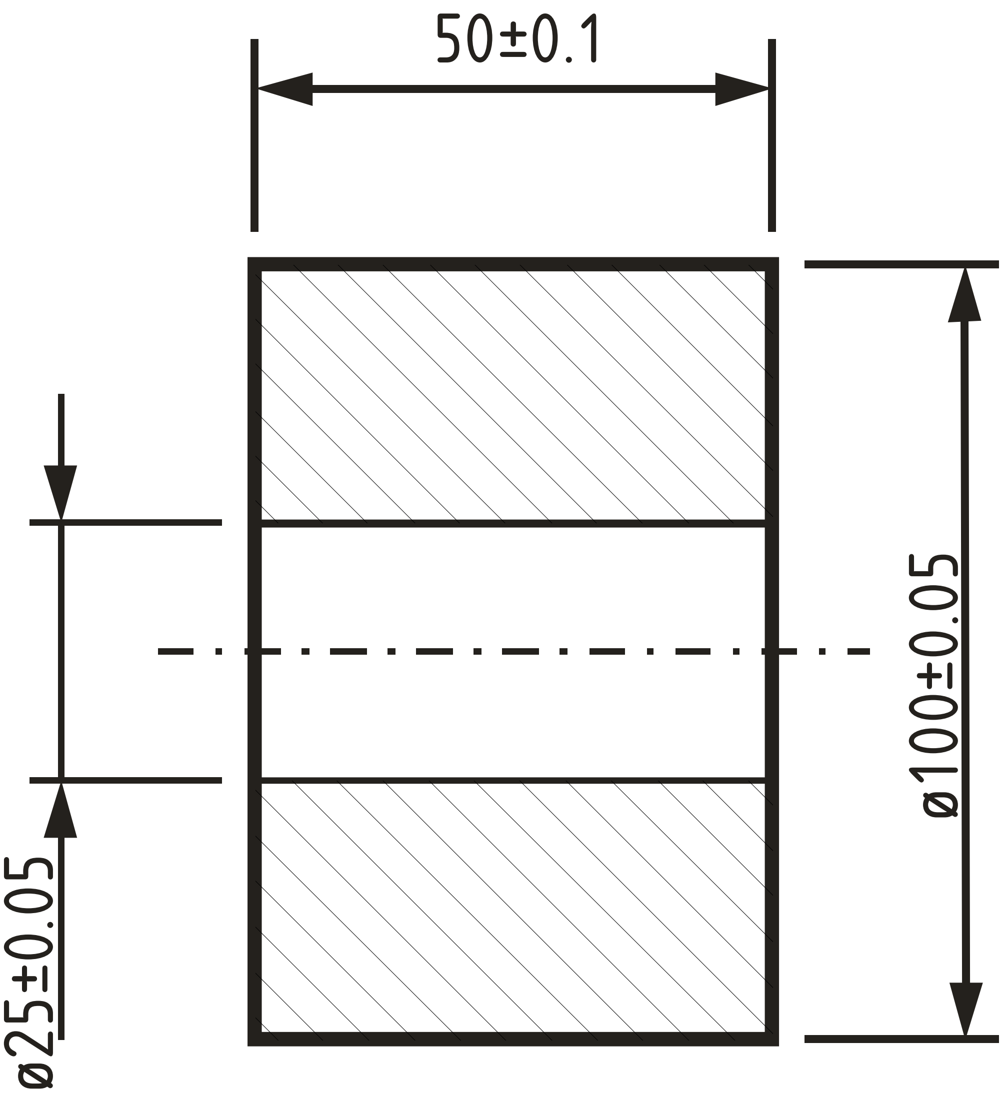
Dimensional Tolerancing

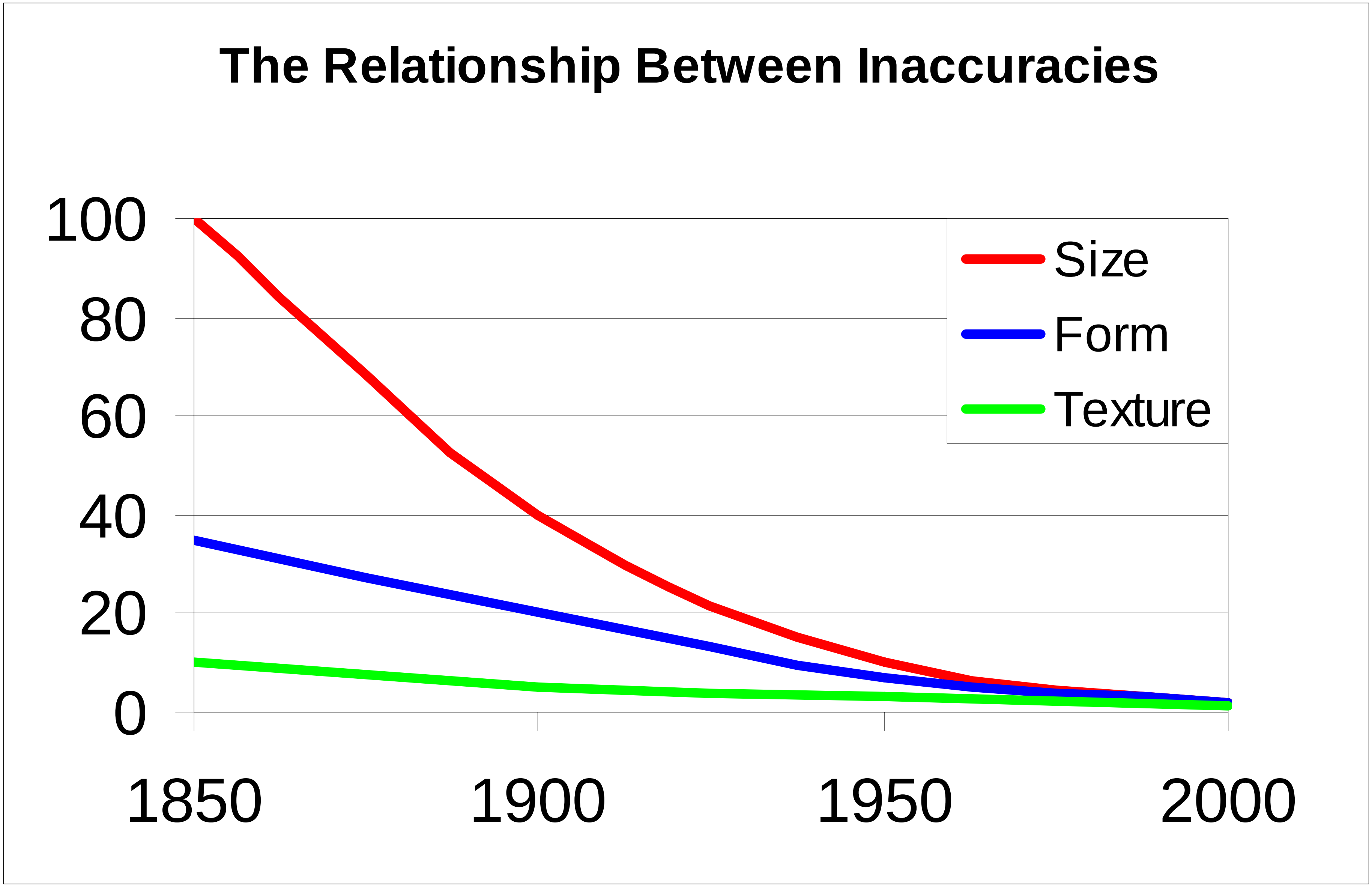
- Individual features controlled
  - OD
  - ID
  - Width (feature of size)
- Relationship between features not controlled
  - Each can move relative to the others
  - Amount of allowable movement not defined



Dimensional Tolerancing

- Dimensional tolerancing works fine as long as:
  - The dimensional tolerances are large compared to the inherent geometrical accuracy of the processes used
  - And the person making the part knows how it is going to be used
- But good luck outsourcing based on this drawing!

Manufacturing Inaccuracies



GD&T

Y14.5 and ISO 1101

- Not measurement standards but fit standards
- Conceptually alike
- Define requirements to multiple features simultaneously
  - Optionally relative to a datum system
  - Can ensure correct location and orientation of features after assembly
  - Significant difference in the details
- Requirements are expressed as zones
  - Zones may be located by datums

The Problems with GD&T

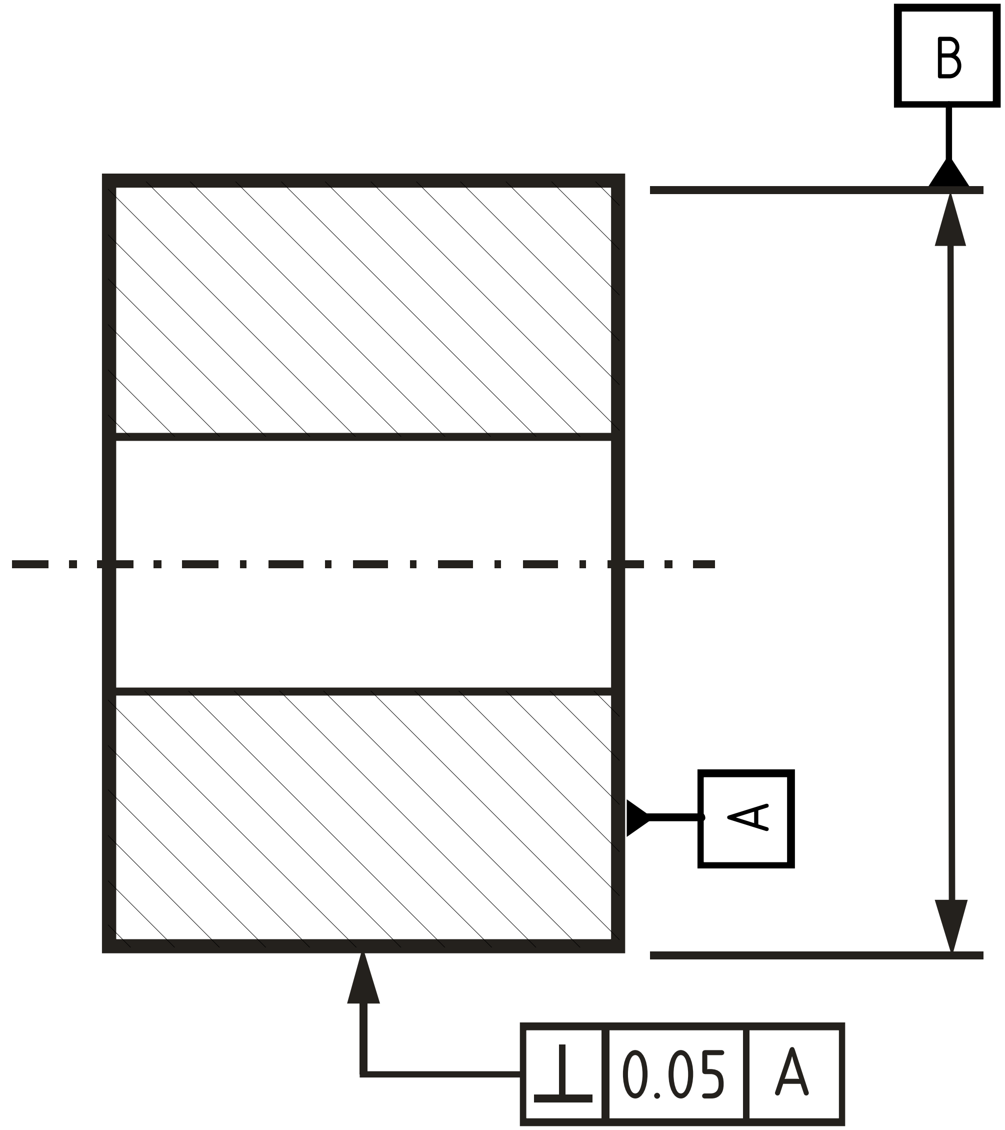
- Generally, only the “vocabulary” and the “grammar” are taught
  - Not “creative writing skills”, i.e. how to tolerance a drawing systematically
- Functional requirements and manufacturing requirements are not separated
  - Makes it hard to read and update the drawing
- CAD systems want to lead people astray
  - Start with dimensions and add GD&T as an afterthought
  - Dimension parts from a (non-functional) corner
- Wavelength content cannot be specified
  - But this is (hopefully) coming soon

The 8 step specification process

- Creative writing instead of disjoined statements added in random order
- Tell a story
  - What is the part supposed to do?
- Should it be measurable?
  - Different kinds of uncertainty

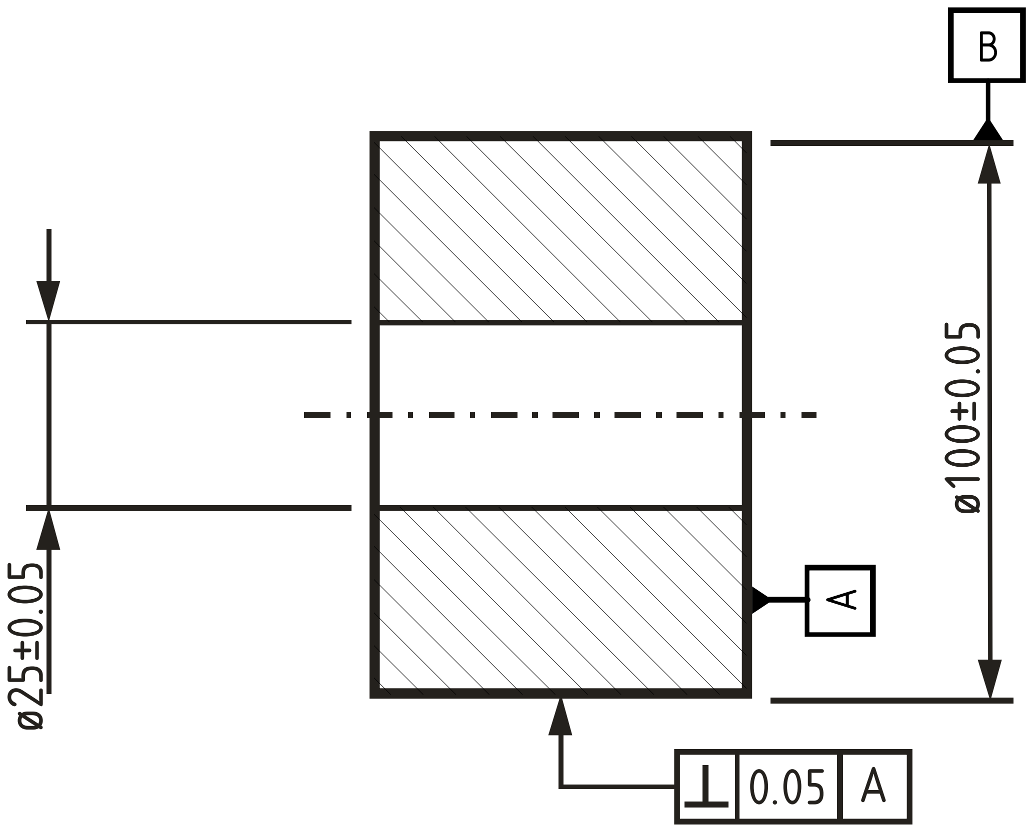
GD&T Step 1
Define the Datum Structure

- Define the datums based on how the part is assembled
- In this case, if datums are used in order:
  - The part's right side is pressed against a surface; then the OD centers the part
- Control how the secondary (and tertiary) datum(s) are related to the primary (and secondary) datums



GD &T Step 2
Tolerance the Fit Features of Size

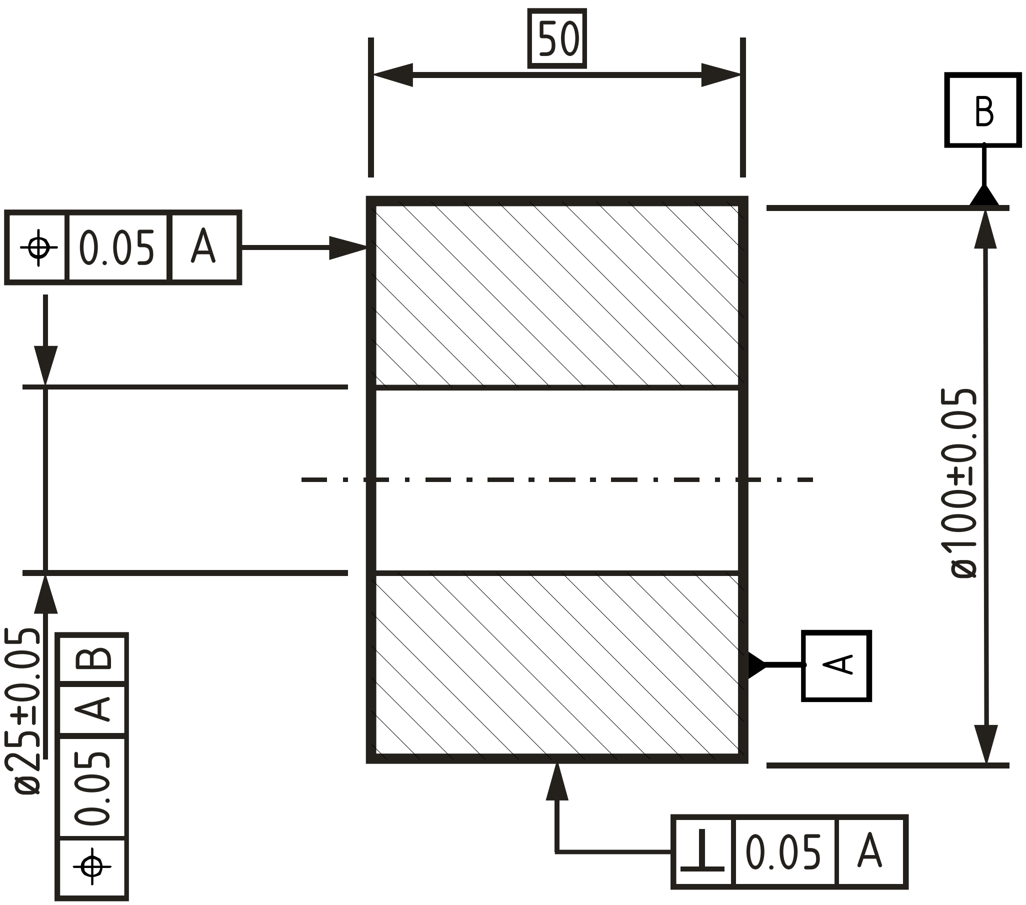
- Tolerance the features of size that are part of fits
- In this case:
  - The OD has to fit with another part, e.g. a housing
  - The ID has to fit with another part, e.g. a shaft



GD&T Step 3

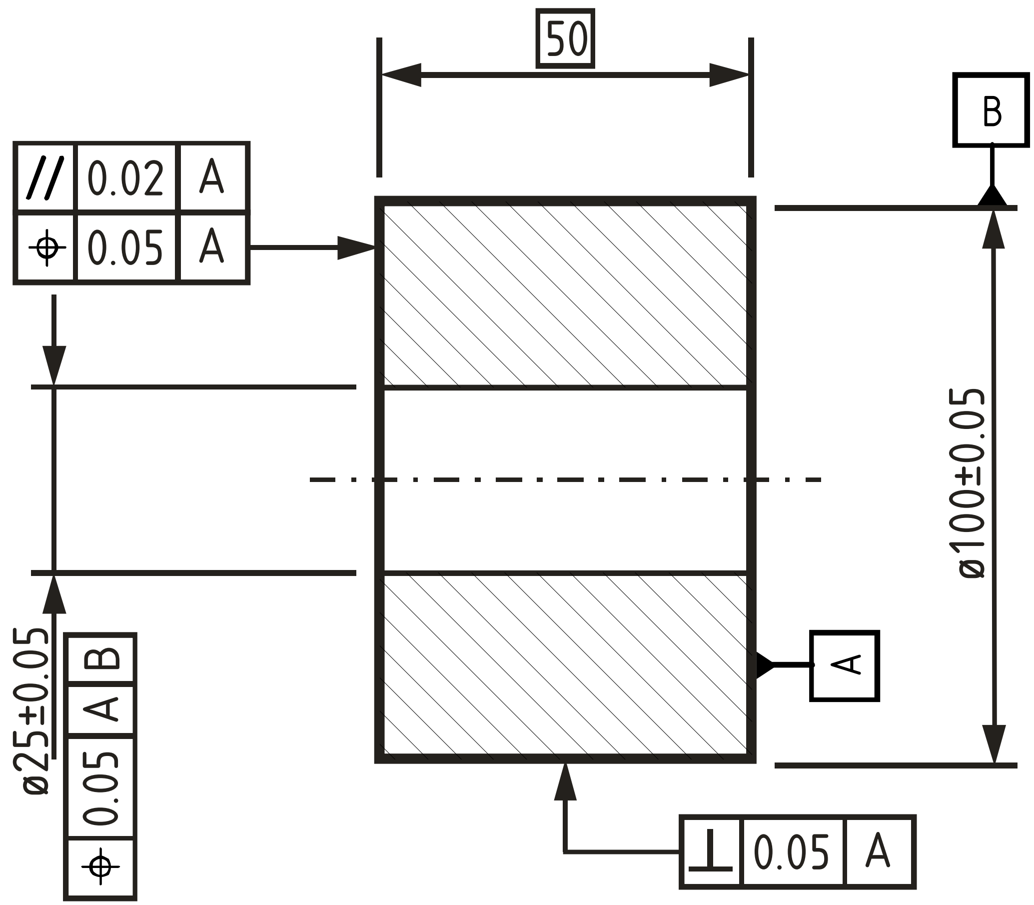
Position Features Relative to the Datum System

- Position other functional features relative to the datum system
- In this case:
  - The left side of the part has to be a fixed distance from the right side of the part
  - The ID has to be perpendicular to the right side and concentric with the OD



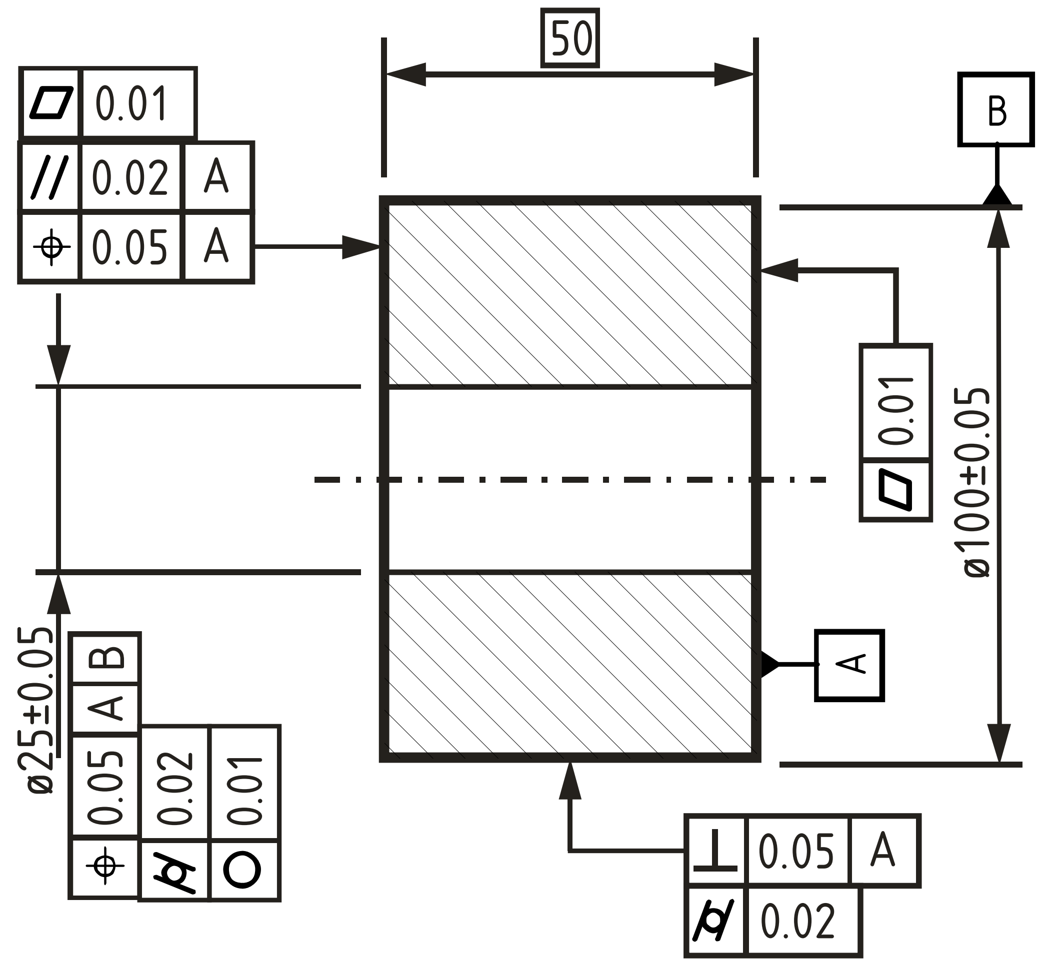
GD&T Step 4
Refine with Orientation Tolerances

- Location tolerances automatically define orientation tolerances
- Refine the requirements to features located relative to the datums with orientation tolerances, as necessary
- The orientation tolerances have to be smaller than the location tolerances in order to add requirements
- In this case
  - The left side of the part has to be parallel to the right side



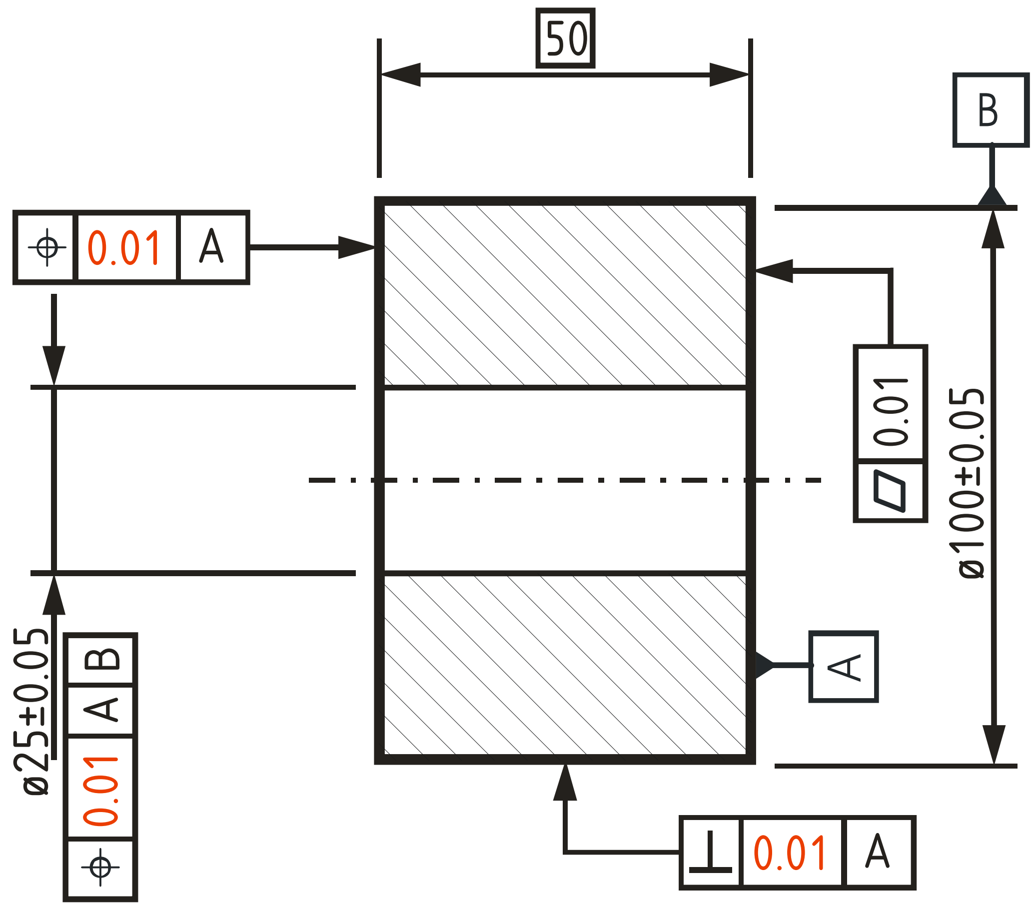
GD&T Step 5
Refine with Form Tolerances

- Location and orientation tolerances automatically define form tolerances
- Refine the requirements with form tolerances, as necessary
- The form tolerances have to be smaller than the location and orientation tolerances in order to add requirements
- In this case
  - The left and right sides of the part have to be flat
  - The OD and ID have to be cylindrical
  - The ID have to be round to a tighter tolerance than the cylindricity



Get real!

- A common objection is that the drawing becomes “too complicated for the real world”
- However, if the drawing represented the true functional requirements it could be replaced by this simpler drawing
  - But the requirements are much tighter



GD&T Step 6-8
Texture and Edges

- Tolerance surface texture
  - Roughness
  - Waviness
- Tolerance surface imperfections
  - Not covered by surface texture
- Tolerance edges

Improving Drawings

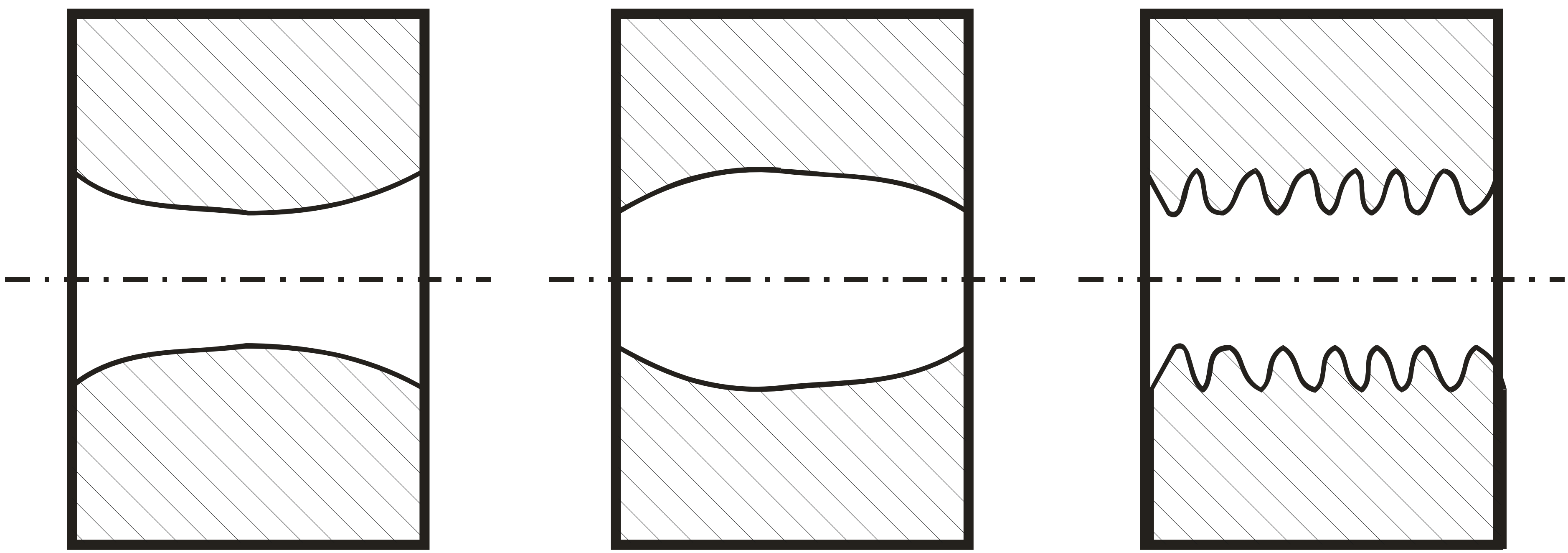
- Applying GD&T systematically according to this process will:
  - Increase the available tolerances
    - Because the the tolerances are specific
  - Make it easier to understand what the part is supposed to do
    - Because it only contains functional requirements
      - Manufacturing drawings can be made subsequently
        - » And changed as manufacturing capabilities change
  - Provide the majority of the potential benefits from improved drawings

GD&T Limitations

- Most requirements are not measurable
  - This is a minor problem
- Most measurement results cannot be expressed as a GD&T requirement
  - This is a MAJOR problem
- Probably the largest limitation in the current GD&T language is that it is not possible to specify which wavelength regime a requirement applies to
  - Y14.5.1 states that requirements applies after the smoothing functions defined in B46 are applied
    - I.e. “roughness” is excluded
  - ISO 1101 does not make any statement

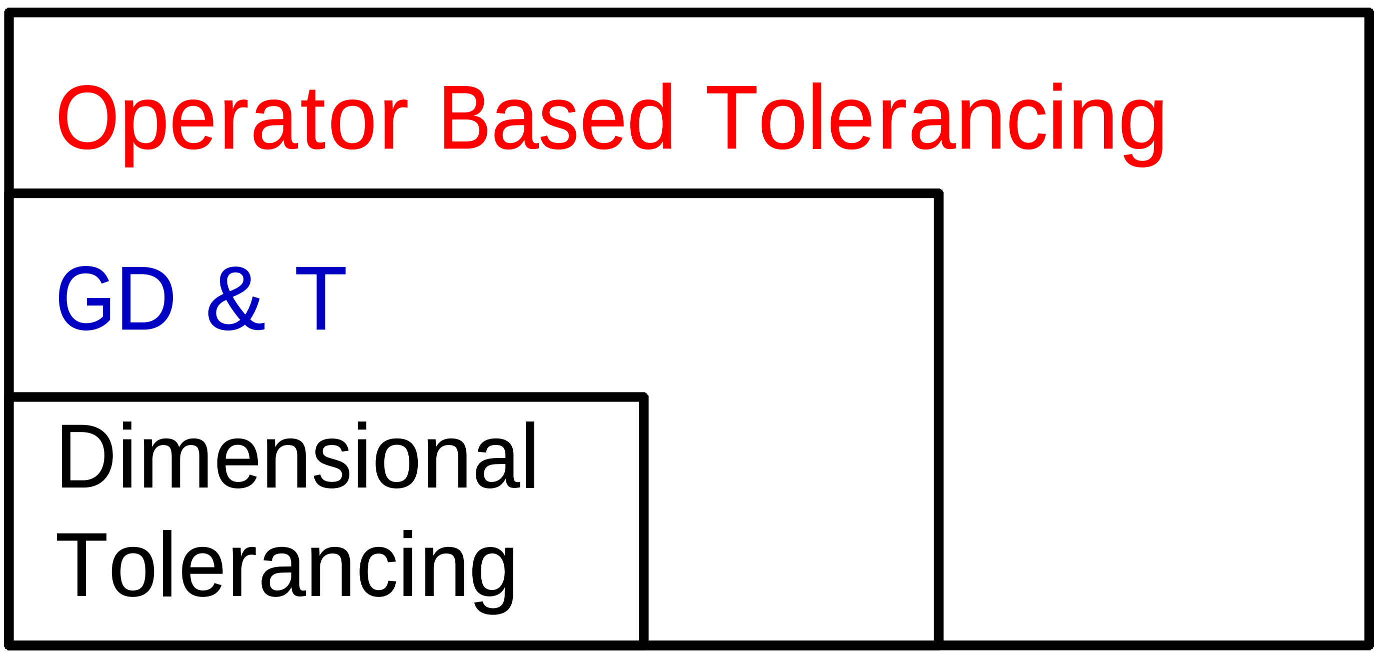
GD&T Limitations

- It is not possible with current GD&T to specify that some of these geometries are acceptable and others are not



GPS - A New Way to Define Requirements

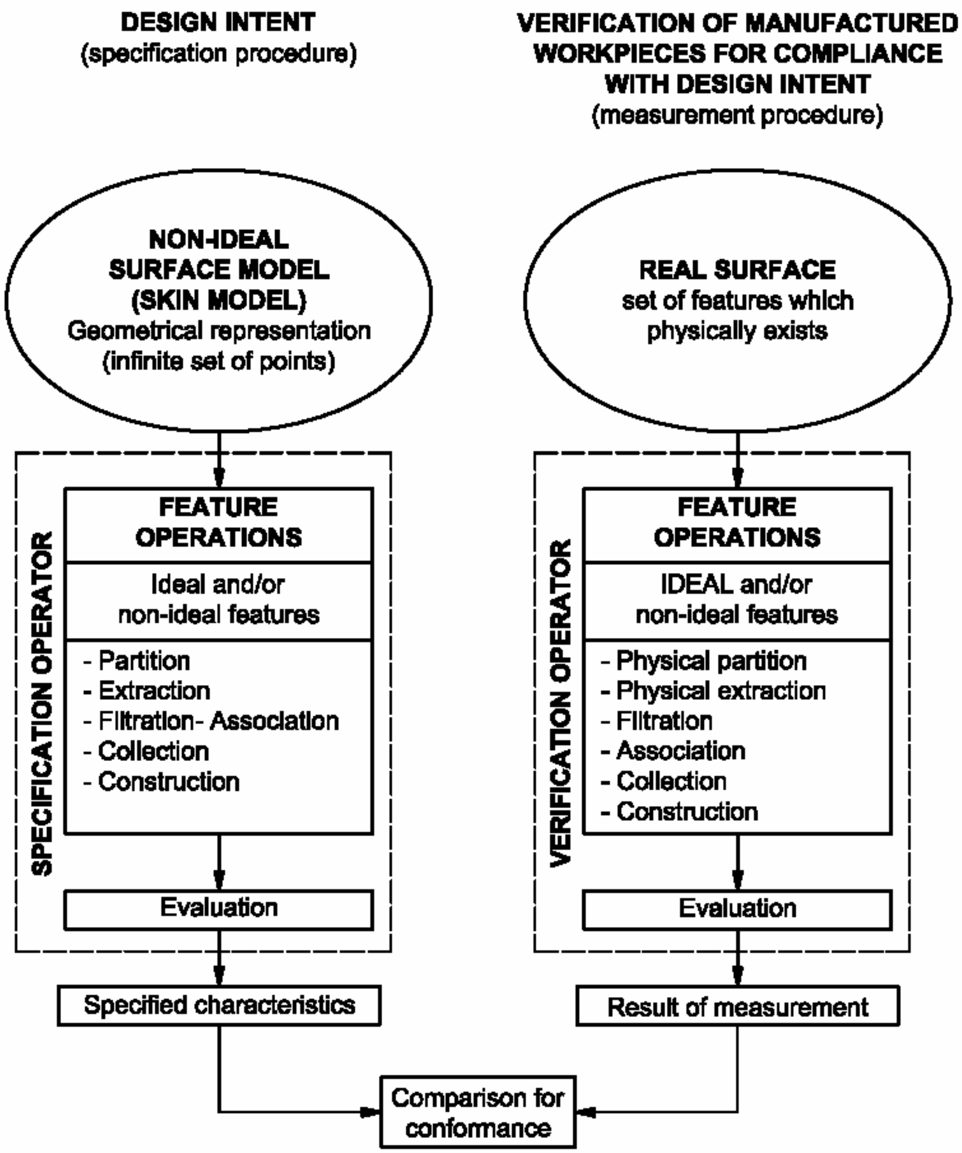
- ISO/TS 17450-1: Geometrical Product Specifications (GPS) — General concepts — Part 1: Model for geometric specification and verification.
- Recipe for virtual measurement
  - partition
  - extraction
  - filtration
  - association
  - collection
  - construction
  - evaluation



2002

Verifying parts against a specification

- The Duality Principle
  – The specification is expressed as an operator
  – The verification (measurement) is expressed as an operator
  – Ideally, the two are identical
  – May be different for practical or economical reasons



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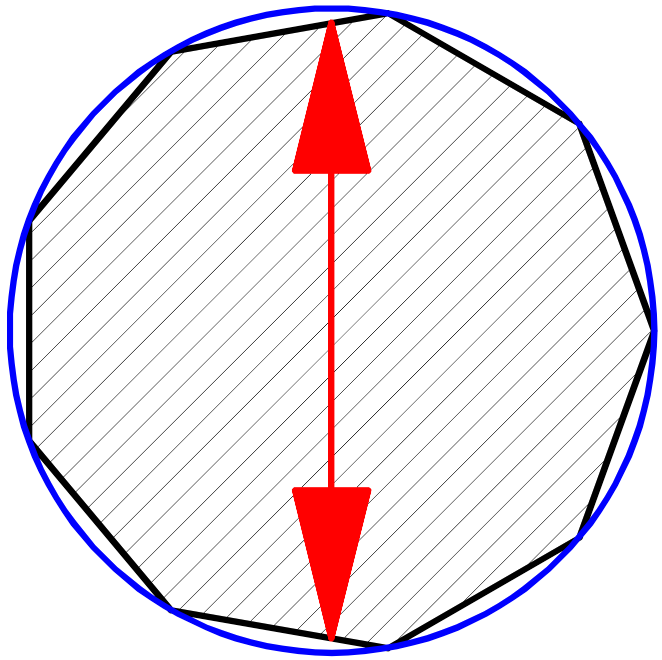
Verifying parts against a specification

- Measurement Uncertainty is made up of:
- Method Uncertainty
  - The measurement method does not reflect the specification operator
  - Minimum circumscribed vs. 2-point diameter
- Implementation Uncertainty
  - Inaccuracies in the measurement equipment and measurement process



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Correlation Uncertainty

- Bearing example:
  - Local peaks will penetrate oil film and cause friction and wear
  - Function requires limitation of the “sharpness” of peaks
  - Specification contains a roundness requirement
  - Because the two are different there is not a 1:1 correlation between measured values and functional performance

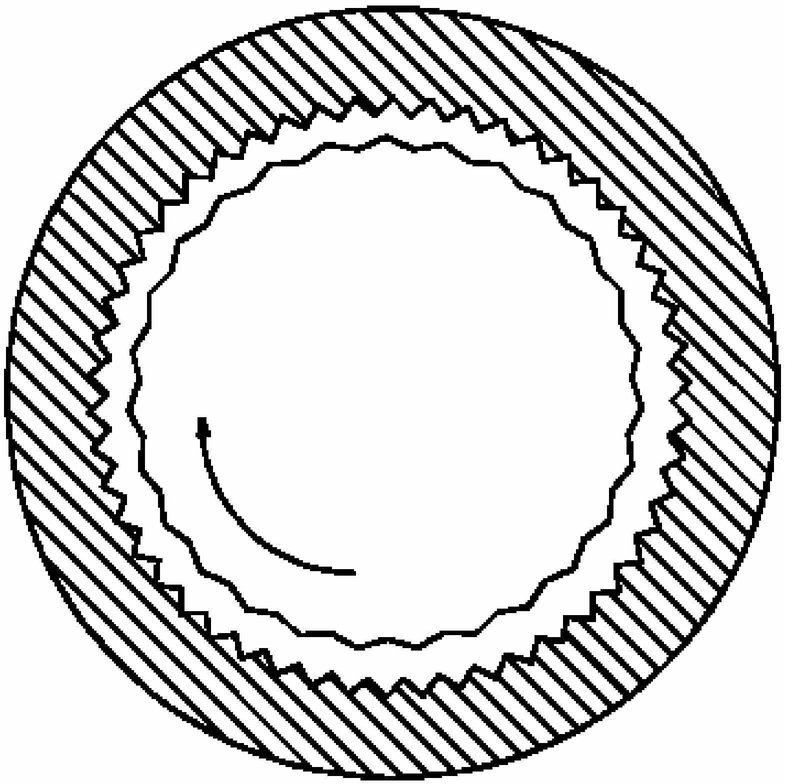
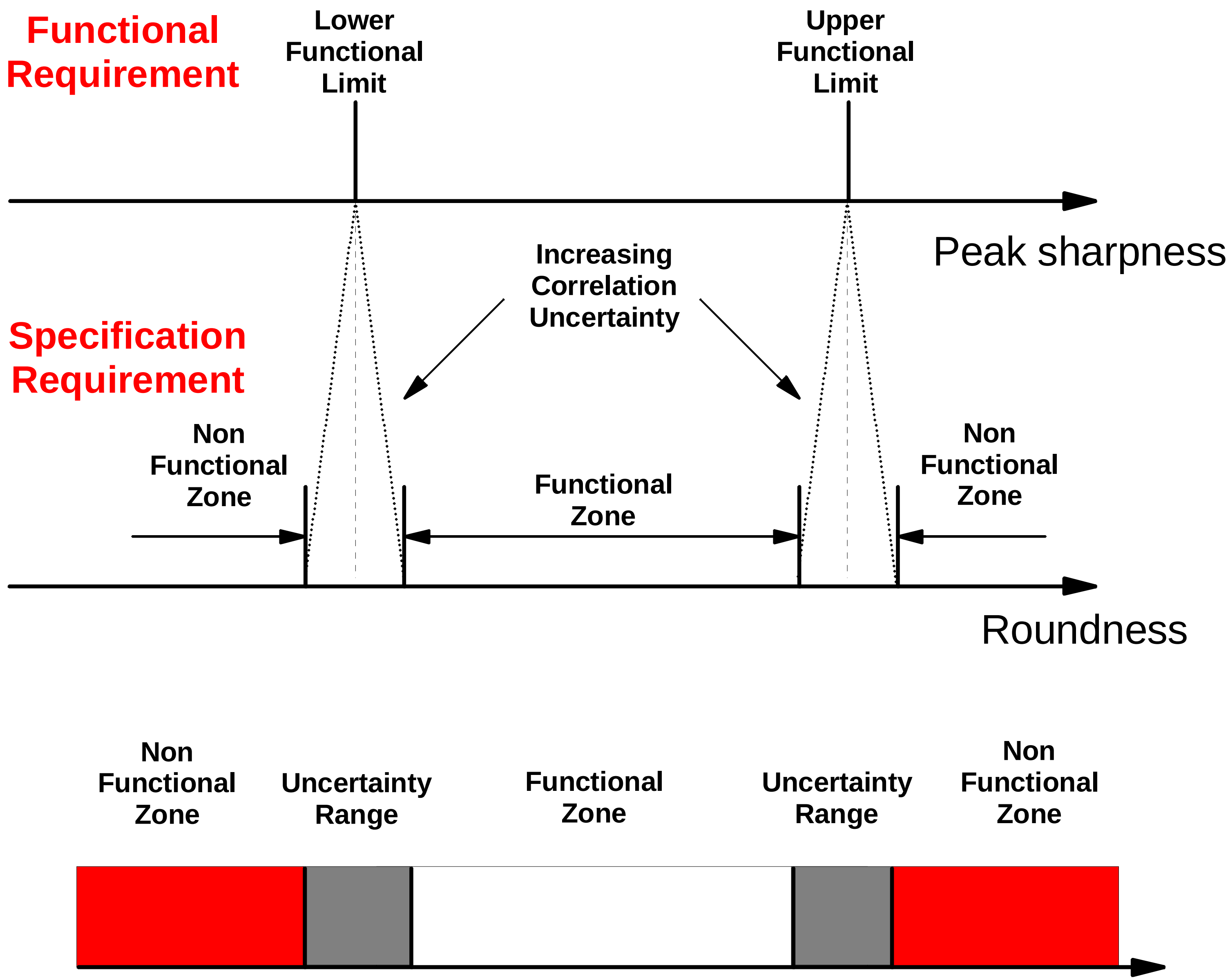


Figure 4: Hydrodynamic sliding bearing

Correlation Uncertainty

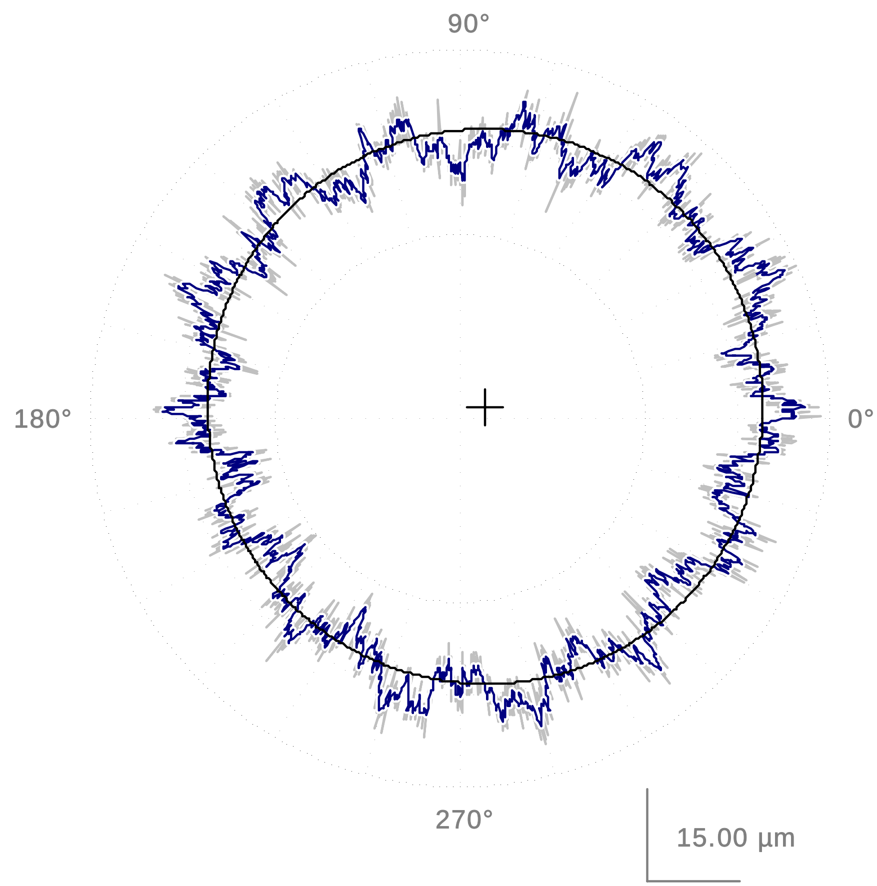


Specification Uncertainty

- Undefined or poorly defined filtering requirements
- Poor definition of the direction in which the requirement applies
- Poor definition of the boundaries of the feature to which the requirement applies

Effects of Filtering
500 UPR

SigmaRound generated data 27 Aug 1999 17:19:06



Gaussian (50%) Filtering: 500 UPR

Reference: Least Squares Circle

Roundness:	16.659	µm
Eccentricity:	4.519	µm
Ecc. Angle:	25.96	deg
Concentricity:	9.038	µm
Runout:	25.558	µm

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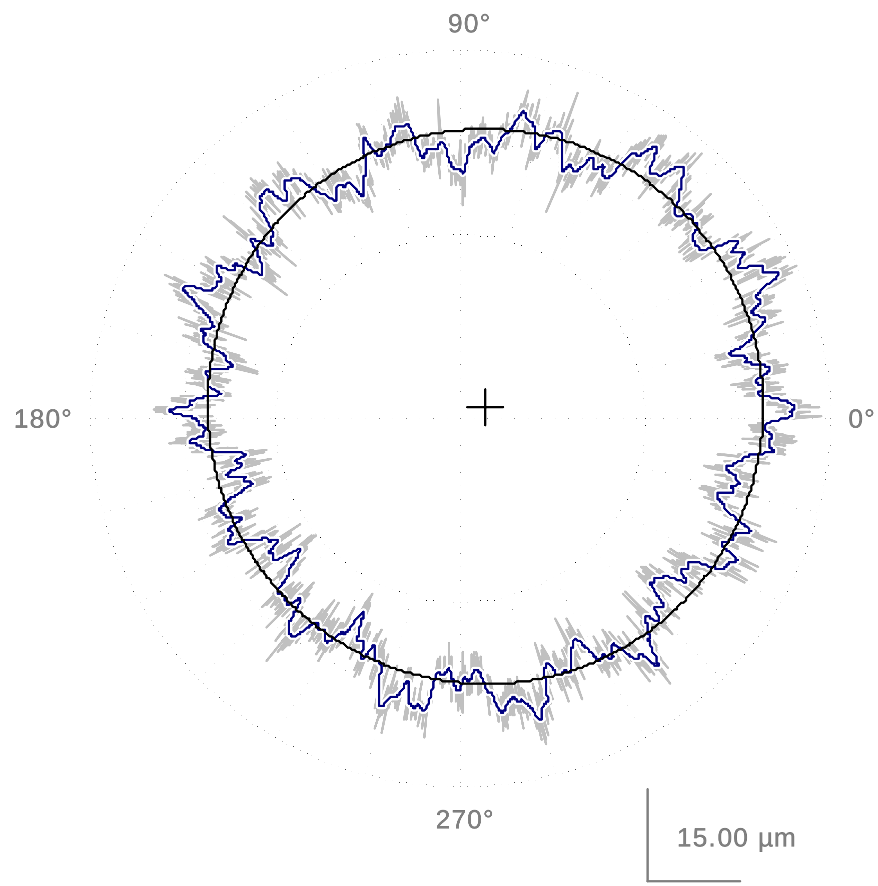
Effects of Filtering 150 UPR

SigmaRound generated data — 27 Aug 1999 17:19:06



Gaussian (50%) Filtering: 150 UPR

Reference: Least Squares Circle

Roundness:	**14.602**	**µm**
Eccentricity:	4.519	µm
Ecc. Angle:	25.96	deg
Concentricity:	9.038	µm
Runout:	23.208	µm

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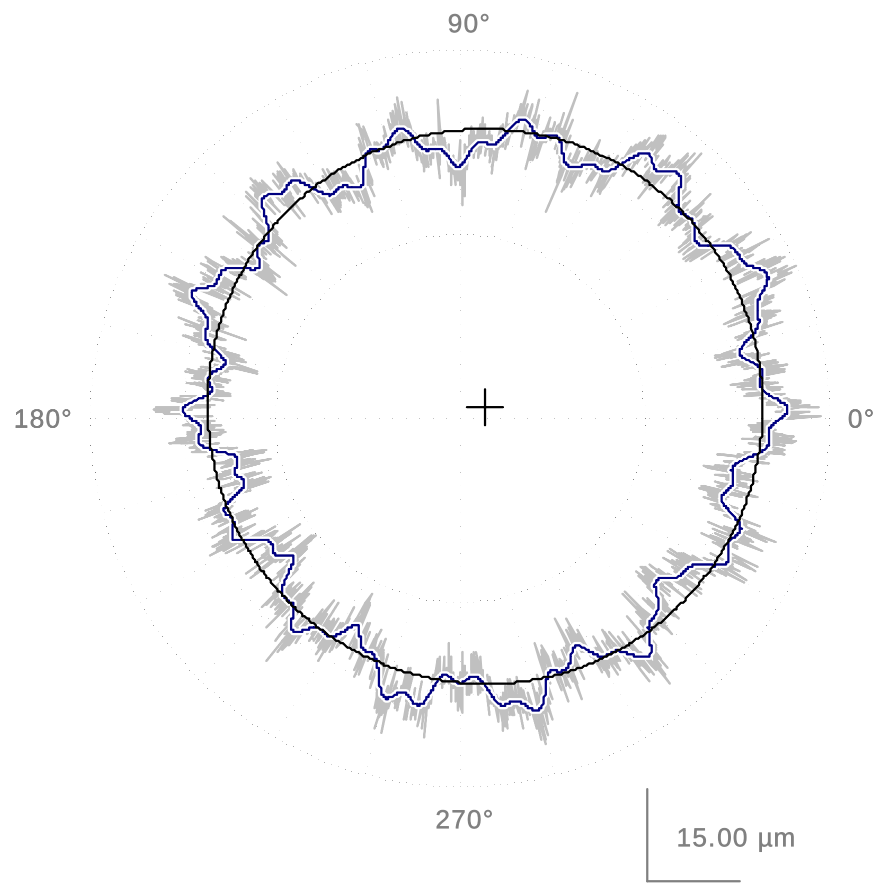
Effects of Filtering
50 UPR

SigmaRound generated data — 27 Aug 1999 17:19:06



Gaussian (50%) Filtering: 50 UPR

Reference: Least Squares Circle

Roundness:	11.899	µm
Eccentricity:	4.519	µm
Ecc. Angle:	25.96	deg
Concentricity:	9.038	µm
Runout:	19.942	µm

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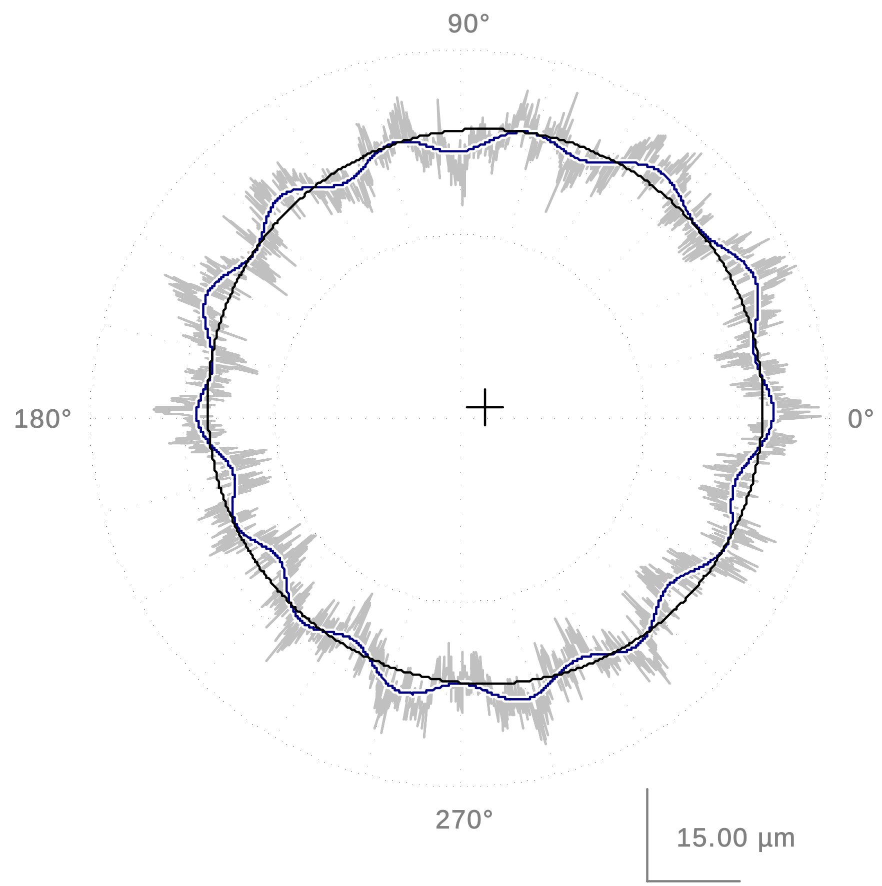
Effects of Filtering 15 UPR

SigmaRound generated data 27 Aug 1999 17:19:06



Gaussian (50%) Filtering: 15 UPR

Reference: Least Squares Circle

Roundness:	**7.119**	**µm**
Eccentricity:	4.519	µm
Ecc. Angle:	25.96	deg
Concentricity:	9.038	µm
Runout:	15.749	µm

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Consequences for Managing Product Geometry

- Zones can be expressed as operators
  - But some information will be missing
  - Well known in metrology
- Inspectors making decisions
  - Due to lack of information
- Uncertain or misleading product documentation

Determining Tolerances and Functional Requirements

- Fit is easy
- Complex workpiece functions
  - Expensive
  - Critical for
    - Performance
    - Reliability
    - Longevity
  - Usually requirements are determined using prototyping
    - Communicate measurement settings to design

Prototyping

- Make parts
- Measure parts
- Test parts
- Determine which parts worked
- Derive tolerance
  - Range of parts that worked
  - Document measurement conditions
    - Not available in current GD&T standards

Prototyping Example 1:

- Part roundness measured using 15 UPR filter
- All parts with a roundness under 8 µm function satisfactory
  - Filter information not included in product documentation

○	0,008

- Production measurements conducted with 150 UPR filter (gives higher values)
- All parts with a roundness over 8 µm rejected
- Many good parts rejected
- Adequate manufacturing process rejected

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Prototyping Example 2:

- Part roundness measured using 150 UPR filter
- All parts with a roundness under 15 µm function satisfactory
  - Filter information not included in product documentation

○	0,015

- Production measurements conducted with 15 UPR filter (gives lower values)
- All parts with a roundness over 15 µm rejected
- Many bad parts accepted

What an Indication Might Look Like

- Roundness 0.01 mm
- RONt = Peak to Valley
- LSCI = From a Least-squares Circle
- G 150 = Gaussian filter with a 150 UPR cut-off

Communicating Functional Requirements

- Richer Language
- Advantages are immense
- Know and understand operations
  - They are not just for the inspector
- Better functional correlation
  - Increase tolerances
  - Avoid acceptance of bad parts
- Less ambiguous specifications
  - Avoid scrapping functional parts
  - Avoid rejecting adequate manufacturing processes

Overkill?
Cost and benefits

- Time to create
  - It probably takes longer to create a functional drawing
    - At least initially
- Editing and revising
  - It is generally easier to revise a drawing, if you know that all the requirements are related to function
- Manufacturing globally
  - The largest obstacle to successful outsourcing of manufactured parts is inadequate product documentation
  - Nobody makes bad parts on purpose

Conclusions

- The operator based GPS system allows for precise and unambiguous expression of requirements for complex workpiece functions
  - Including those determined based on prototyping
  - New terms such as “Specification Uncertainty” facilitates communication
- The expression of simple requirements, e.g. fit, does not get any more complex
- Dismiss detailed definitions as “measurement details” and be a liability
- Embrace these new tools and be an asset

Conclusions

- The extra effort it takes in the design phase to understand the operator-based system and apply precise, functional requirements is insignificant compared to the immense potential savings in the manufacturing and support phase of the product lifecycle.