Topic 08

University Mechanical Engineering

What this course is, and how to use it

This is the eighth course in University Mechanical Engineering: **manufacturing processes** – how a drawing becomes a part: how the part is specified, which process shapes it, what each process costs in time, force and accuracy, and how we prove the parts are good. The parts are the pump housing, shaft and bracket of the cooling loop from Courses 6 and 7.

Scope limit, stated once: a study course, not a degree; there is no workshop. The process numbers (flow stresses, tool-life constants, mould constants) are typical teaching values, stated where used, and every number printed here is recomputed in the course suite.

- Unit 8.1 writes the part down: drawings, fits and tolerance stacks.
- Units 8.2–8.4 make it: casting and forming, machining, joining.
- Unit 8.5 adds the newest route: additive manufacturing.
- Unit 8.6 plans the route and proves the result: capability and control.

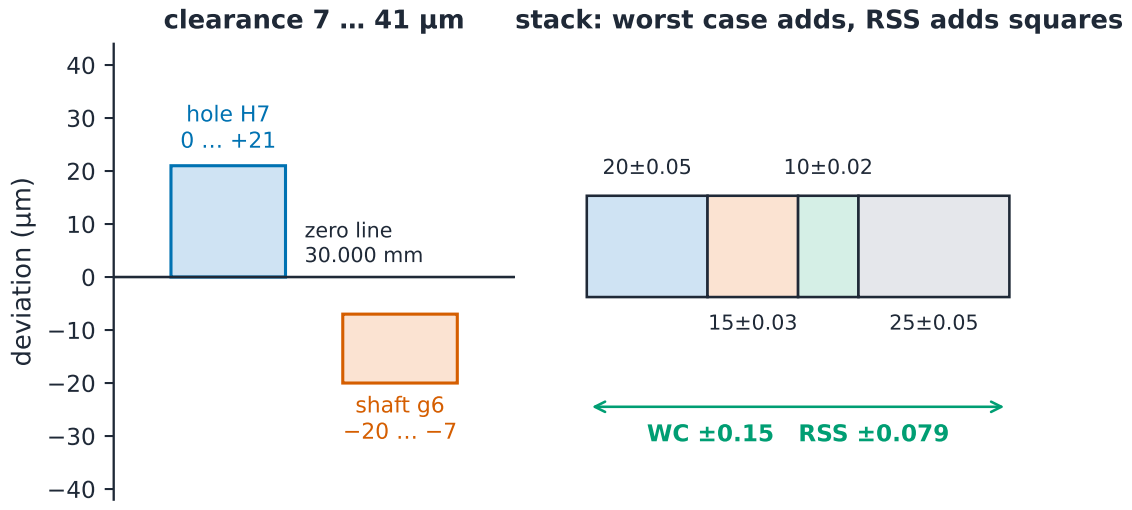
The habit: **every process has a time, a force and a tolerance** – choose the process by computing all three, not by habit.

Engineering drawings and tolerances

Why it matters. The pump shaft must turn freely in its bearing housing, but not rattle. "About 30 mm" cannot say that; a **tolerance** and a **fit** can.

The idea, with a picture. An **engineering drawing** uses **orthographic views** (front, top, side, plus sections where the inside matters) and measures every feature from a **datum** – a surface the part is located by. Each size carries limits. ISO fits combine a hole tolerance and a shaft tolerance. In the **hole-basis system**, the hole is H (lower deviation zero) and the letter of the shaft sets the kind of fit.

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A hole-basis fit as tolerance zones, and a four-part stack-up priced worst case and by RSS

The derivation (worst case versus RSS). If a gap is set by n parts in a chain, its worst-case tolerance is the sum $T_{WC} = \sum t_i$: every part at its worst limit at the same time. If the parts' errors are independent and centred, their variances add, so the statistical tolerance is the **root sum of squares** $T_{RSS} = \sqrt{\sum t_i^2}$ – smaller, because all-worst-at-once is rare.

> **Worked example 1 – the shaft fit.** The pump shaft is **30 H7/g6**. From the ISO tables: hole 30.000 to 30.021 mm (H7: 0 to +21 µm); shaft 29.980 to 29.993 mm (g6: −20 to −7 µm). Maximum clearance = 30.021 − 29.980 = **41** µm; minimum clearance = 30.000 − 29.993 = **7** µm. Always positive, so this is a **clearance fit** – the shaft turns, with at most 41 µm of play.

> **Worked example 2 – the stack-up.** Four spacers of 20 ± 0.05, 15 ± 0.03, 10 ± 0.02 and 25 ± 0.05 mm stack along the shaft. Worst case: $\pm(0.05 + 0.03 + 0.02 + 0.05) = \pm\mathbf{0.15}$ mm. RSS: $\pm\sqrt{0.05^2 + 0.03^2 + 0.02^2 + 0.05^2} = \pm\mathbf{0.079}$ mm. If the housing bore depth adds ±0.04, the gap tolerance is ±**0.19** worst case and ±**0.089** RSS. Use worst case when one failure is unacceptable; use RSS for high volume with capable processes.

Common mistakes. Measuring from an edge that is not the datum. Adding RSS tolerances for a safety-critical one-off. Reading H7/g6 as an interference fit (the letters g and h give clearance; p, s and u give interference).

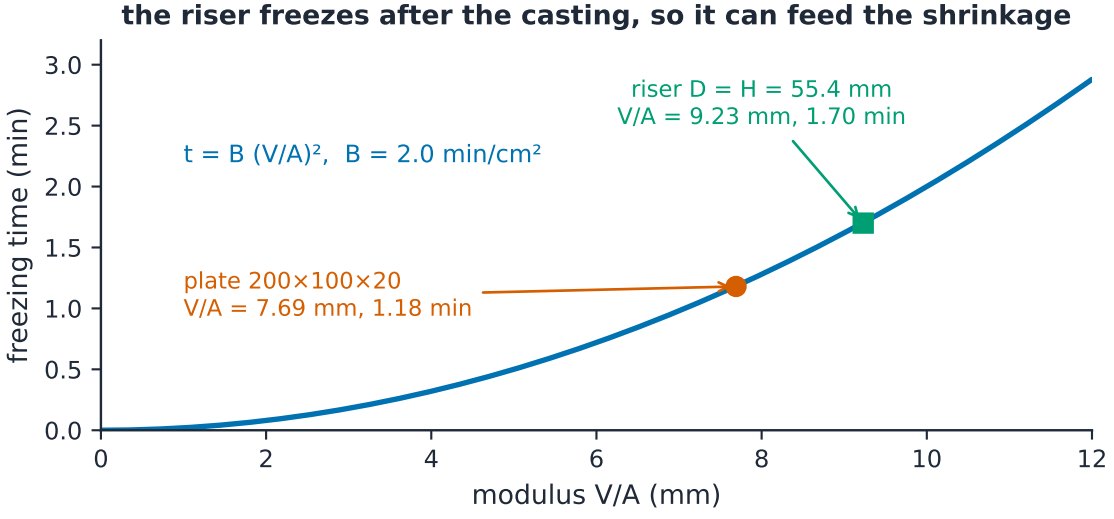
Summary. Views, sections and datums carry the geometry; fits pair a hole and a shaft tolerance; $T_{WC} = \sum t_i$, $T_{RSS} = \sqrt{\sum t_i^2}$.

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Casting and forming

Why it matters. The pump housing is cast and the shaft stock is drawn. Casting gives complex shapes in one step. Forming gives strength and good surfaces. Each has a physical limit that the designer must respect.

The idea, with a picture. In **casting** , molten metal fills a mould and solidifies. **Chvorinov's rule** gives the freezing time: $t = B\,(V/A)^2$, where V/A is the **casting modulus** . Metal shrinks as it freezes, so a **riser** must freeze last and feed the casting. **Forming** (forging, rolling, extrusion, drawing) shapes solid metal by plastic flow. The force is set by the **flow stress** $\sigma_f = K\varepsilon^n$.



Chvorinov's rule: the riser has the larger modulus, so it freezes last and feeds the casting

The derivation (the ideal drawing stress). In wire drawing, the plastic work per unit volume is $\int \sigma_f \, d\varepsilon = \bar{Y}\varepsilon$, with true strain $\varepsilon = \ln(A_0/A_f)$ and average flow stress $\bar{Y} = K\varepsilon^n/(1+n)$. This work is done by the drawing stress acting on the exit area, so $\sigma_d = \bar{Y}\ln(A_0/A_f)$. The wire breaks if σ_d reaches the flow stress of the drawn wire. For an ideal process that gives the limit $\varepsilon_{max} = 1 + n$ (about 70% area reduction when $n = 0.2$). Real dies, with friction, allow less.

> **Worked example 1 – the plate and its riser.** A steel plate casting $200 \times 100 \times 20$ mm: $V = 400\,000$ mm^3, $A = 52\,000$ mm^2, modulus $V/A =$ **7.69** mm. With $B = 2.0$ min/cm^2: $t = 2.0 \times 0.769^2 =$ **1.18** min. A cylindrical riser with $D = H$ has $V/A = D/6$. To freeze 20% later in modulus terms it needs $D/6 = 1.2 \times 7.69$, so $D =$ **55.4** mm, freezing in **1.70** min.

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Worked example 2 – drawing the shaft wire. Draw 6 mm wire to 5 mm ($K = 500$ MPa, $n = 0.2$). $\varepsilon = \ln(36/25) = \mathbf{0.365}$; $\bar{Y} = 500 \times 0.365^{0.2}/1.2 = \mathbf{341}$ MPa; $\sigma_d = 341 \times 0.365 = \mathbf{124}$ MPa; force $= 124 \times \pi \times 2.5^2 = \mathbf{2.44}$ kN. The drawn wire's flow stress is $500 \times 0.365^{0.2} = 409$ MPa, so σ_d is only 30% of it – a safe pass with room for friction.

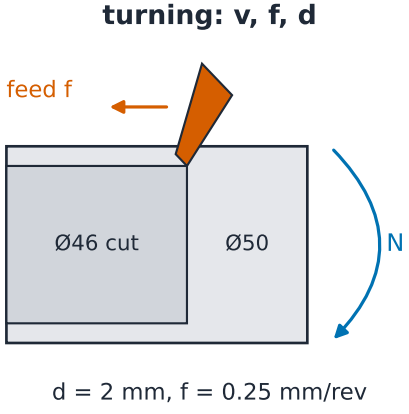
Common mistakes. Using volume alone in Chvorinov (shape matters through A). Putting the riser where it freezes before the casting. Using engineering strain in forming calculations (use true strain, ln).

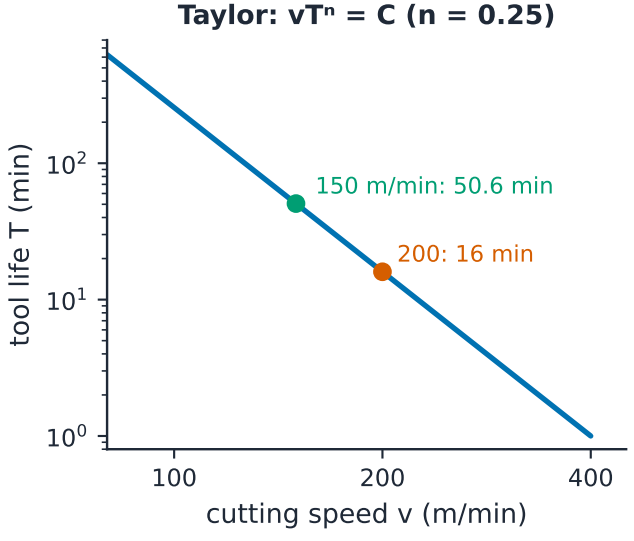
Summary. $t = B(V/A)^2$; the riser's modulus must be larger; $\sigma_d = \bar{Y}\ln(A_0/A_f)$ with $\bar{Y} = K\varepsilon^n/(1+n)$; ideal limit $\varepsilon = 1 + n$.

Machining

Why it matters. The shaft's bearing seats need ±10 µm and a fine finish that no casting can give. **Machining** removes metal to get there, and every second and every tool edge costs money.

The idea, with a picture. In turning, the work spins at N rpm and the tool moves along it. Three settings control the cut: **cutting speed** $v = \pi DN$, **feed** f (mm per revolution) and **depth of cut** d. From them: **material removal rate** $\text{MRR} = vfd$, power $P = u \cdot \text{MRR}$ (with specific energy u), and time $t = L/(fN)$. The tool wears. **Taylor's tool-life equation** $vT^n = C$ says that faster cutting shortens tool life sharply.





Turning sets speed, feed and depth; Taylor's line trades cutting speed against tool life

The derivation (why roughness grows as f^2). A tool with nose radius r leaves a series of arcs spaced f apart. The height of each scallop is about $f^2/(8r)$, and the arithmetic mean roughness is about a quarter of that: $R_a \approx f^2/(32r)$. Halving the

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feed quarters the roughness – but doubles the cutting time.

> **Worked example 1 – one pass on the shaft.** Turn a 50 mm steel bar at $v = 150$ m/min, $f = 0.25$ mm/rev, $d = 2$ mm over $L = 200$ mm. $N = 1000v/(\pi D) =$ **955** rpm; MRR $= 150\,000 \times 0.25 \times 2 = 75\,000$ mm^3/min $=$ **1250** mm^3/s; with $u = 2.8$ J/mm^3, power $=$ **3.5** kW; time $= 200/(0.25 \times 955) =$ **0.84** min. With a 0.8 mm nose radius, $R_a \approx 0.25^2/(32 \times 0.8)$ mm $=$ **2.44** µm.

> **Worked example 2 – the speed trade-off.** With $n = 0.25$ and $C = 400$: at 150 m/min, $T = (400/150)^4 =$ **50.6** min of cutting per edge, about 60 shafts. At 200 m/min, $T =$ **16.0** min. Each pass is now 25% faster (0.63 min), but the edge lasts only 25 shafts. Whether the faster speed pays depends on the cost of tool changes against the cost of machine time.

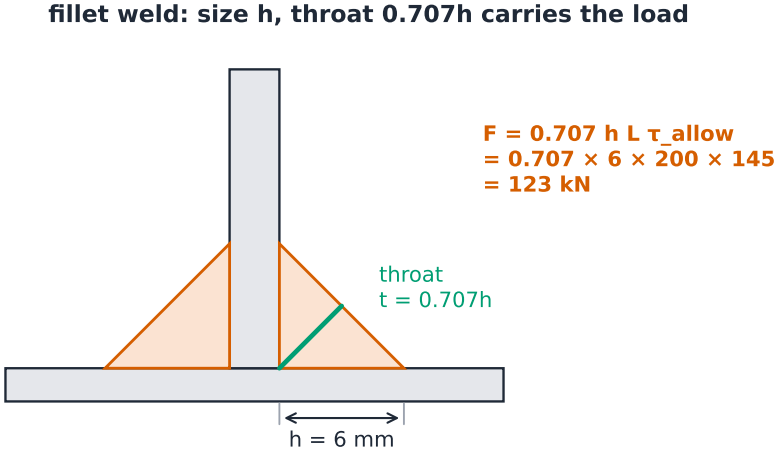
Common mistakes. Using the finished diameter for N (use the diameter being cut). Mixing m/min and mm/s in MRR. Assuming a higher speed always lowers cost.

Summary. $v = \pi DN$, MRR $= vfd$, $P = u\cdot$MRR, $t = L/(fN)$; $vT^n = C$; $R_a \approx f^2/32r$.

Joining

Why it matters. The pump bracket is welded to the base frame, and its cover is glued. A joint is usually the weakest place in an assembly, so it is sized on purpose, not by eye.

The idea, with a picture. **Welding** melts and fuses the parent metal. The **heat input** $H = \eta V I/v$ (J/mm) controls the size of the weld and how much the heat damages the nearby metal. A **fillet weld** fails in shear through its **throat**, the shortest path across the weld: $t = 0.707h$ for leg size h. **Adhesive bonding** spreads the load over an area and is strongest in shear, weakest in peel.



A fillet weld fails through its throat, 0.707 times the leg size

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The derivation (why 0.707). An equal-leg fillet is a right-angled triangle with legs h. The shortest line from the root to the face is the height onto the hypotenuse: $h \sin 45° = 0.707h$. Shear stress on that plane is $\tau = F/(0.707hL)$.

> **Worked example 1 – the bracket welds.** Two fillet welds, each $L = 100$ mm long, leg $h = 6$ mm, E70 electrode ($S_{ut} = 482$ MPa, allowable shear $0.3S_{ut} = 145$ MPa): $F = 0.707 \times 6 \times 200 \times 145 = \mathbf{123}$ kN. The heat input with $\eta = 0.8$, 25 V, 200 A at 5 mm/s is $H = 0.8 \times 25 \times 200/5 = \mathbf{800}$ J/mm – a normal value for 6 mm fillets on steel.

> **Worked example 2 – the bonded cover.** A single-lap bond 25×12.5 mm with an epoxy of average shear strength 20 MPa carries $20 \times 312.5 = \mathbf{6.25}$ kN. But the stress peaks at the ends of the overlap, so doubling the overlap length does not double the strength. Design the joint so that peel is avoided.

Common mistakes. Using the leg h instead of the throat $0.707h$. Ignoring the heat-affected zone in hardened steel. Loading a bonded joint in peel.

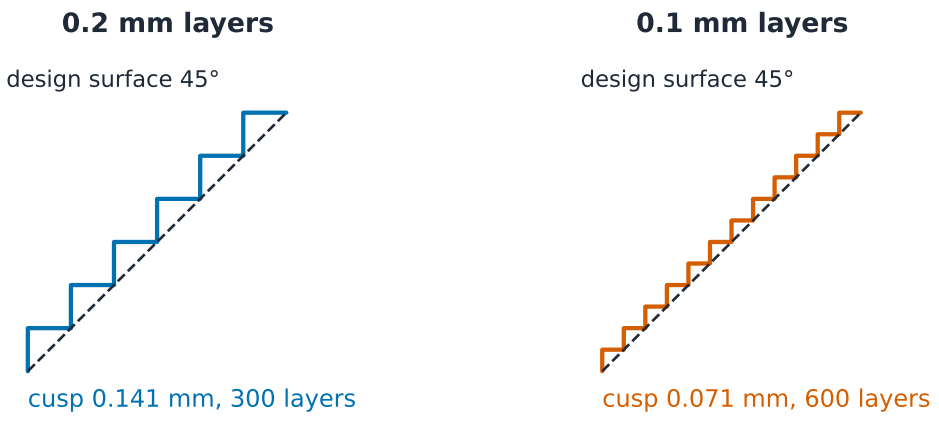
Summary. $H = \eta VI/v$; fillet throat $0.707h$; $F = 0.707hL\tau_{allow}$; adhesives in shear, never in peel.

Additive manufacturing

Why it matters. A custom flow-straightener for the loop has internal channels that no tool can reach. **Additive manufacturing** builds the part layer by layer, so it makes such shapes easily – but layers bring their own limits.

The idea, with a picture. Main families: material extrusion (FDM), powder bed fusion (SLS, metal LPBF), vat photopolymerisation (SLA) and binder jetting. All of them slice the model into layers of thickness t. A sloped surface then becomes a **staircase effect**, with **cusp height** $c = t\cos\theta$, where θ is the angle between the surface normal and the build direction (flat and vertical faces have no cusp). Parts are usually weaker across the layers than along them (**anisotropy**).

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Stair-stepping on a 45° wall: halving the layer halves the cusp and doubles the layer count

The derivation (layer count sets time). Build time is roughly the number of layers times the time per layer: $t_{build} \approx (H/t) \cdot t_{layer}$. Halving t halves the cusp, but it doubles the layers and so roughly doubles the time. Accuracy and speed trade directly.

> **Worked example 1 – layer choice.** The straightener is 60 mm tall. At 0.2 mm layers: **300** layers, and a 45° wall has $c = 0.2 \cos 45° = \mathbf{0.141}$ mm. At 0.1 mm: **600** layers and $c = \mathbf{0.071}$ mm – twice the time for half the roughness. Orienting the wall vertical removes the cusp entirely, so orientation is the first lever.

> **Worked example 2 – print or machine?** Printing costs about €40 per part with no set-up. Machining a simpler two-part version costs €400 of set-up plus €12 per part. Break-even: $400/(40 - 12) = \mathbf{14.3}$, so printing wins up to 14 parts and machining from 15. Above that, the internal channels must justify the extra cost.

Common mistakes. Choosing orientation last instead of first. Ignoring support removal and post-machining in the cost. Assuming a printed part has the bulk material's properties in every direction.

Summary. Layers make a staircase, $c = t \cos\theta$; time scales with H/t; orientation first; break-even $N =$ set-up/(AM cost − unit cost).

Process planning and quality

Why it matters. A drawing and a process are not enough – the shop must show that the process *keeps* making parts inside the tolerance. **Process capability** and **statistical process control** give that proof.

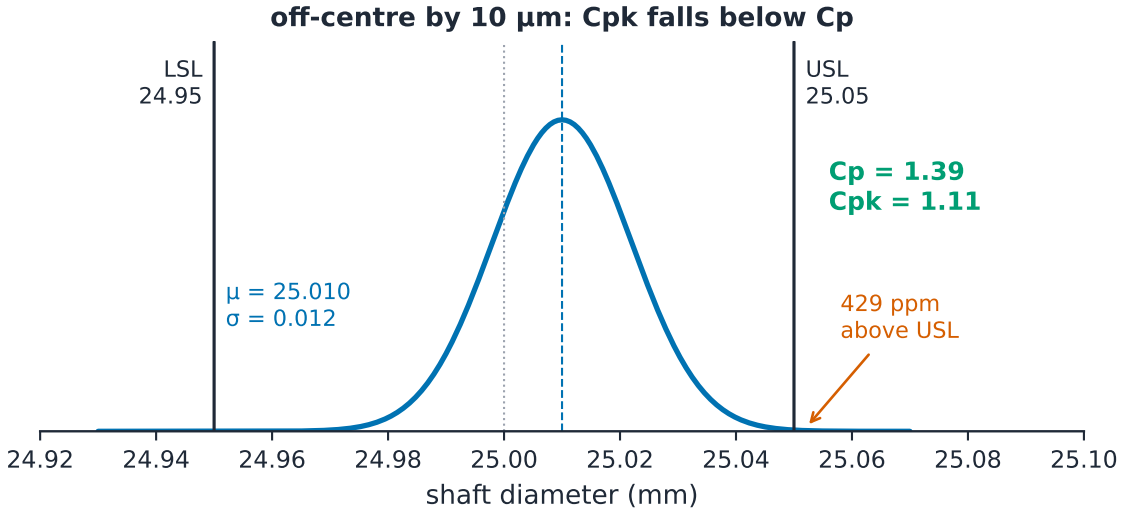
The idea, with a picture. A **process plan** lists the operations in order (stock → rough turn → heat treat → finish grind → inspect) and gives each one a

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datum and a tolerance. The capability indices compare the process spread 6σ with the tolerance width:

$$C_p = \frac{USL - LSL}{6\sigma}, \qquad C_{pk} = \frac{\min(USL - \mu,\ \mu - LSL)}{3\sigma}$$

C_p asks whether the spread fits; C_{pk} also asks whether it is centred.



Process spread against the specification limits: an off-centre mean lowers Cpk

The derivation (indices to defect rate). For a normal process, the distance from the mean to the nearer limit is $3C_{pk}$ standard deviations. So the defect fraction beyond that limit is $1 - \Phi(3C_{pk})$. A centred process with $C_p = 1.33$ gives about 63 ppm; with $C_{pk} = 1.11$, the nearer tail alone is several hundred ppm.

> **Worked example 1 – the bearing seat.** Specification 25.00 ± 0.05 mm; the grinder runs at $\mu = 25.010$, $\sigma = 0.012$ mm. $C_p = 0.10/0.072 =$ **1.39** – the spread fits. $C_{pk} = 0.040/0.036 =$ **1.11** – the 10 µm offset costs capability. Above USL: $z = 3.33$, **429** ppm. Re-centring the grinder to 25.000 gives $C_{pk} = 1.39$ and only **31** ppm in total – a set-up fix, no new machine.

> **Worked example 2 – the control chart.** To keep it centred, the operator samples $n = 5$ shafts each hour and plots the mean on an $\bar{x}$ chart with limits $\mu \pm 3\sigma/\sqrt{n} = 25.010 \pm 0.016$, i.e. **24.994** to **25.026** mm. A point outside the limits (or a run of seven on one side) means the process has changed – stop and find the cause before scrap appears.

Common mistakes. Quoting C_p for an off-centre process. Using specification limits as control limits (they answer different questions). Computing σ from a few parts measured on a gauge coarser than a tenth of the tolerance.

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Summary. Plan each operation with its datum; C_p for spread, C_{pk} for spread and centring; defects $\approx 1-\Phi(3C_{pk})$; $\bar{x}$ limits $\mu \pm 3\sigma/\sqrt{n}$.

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