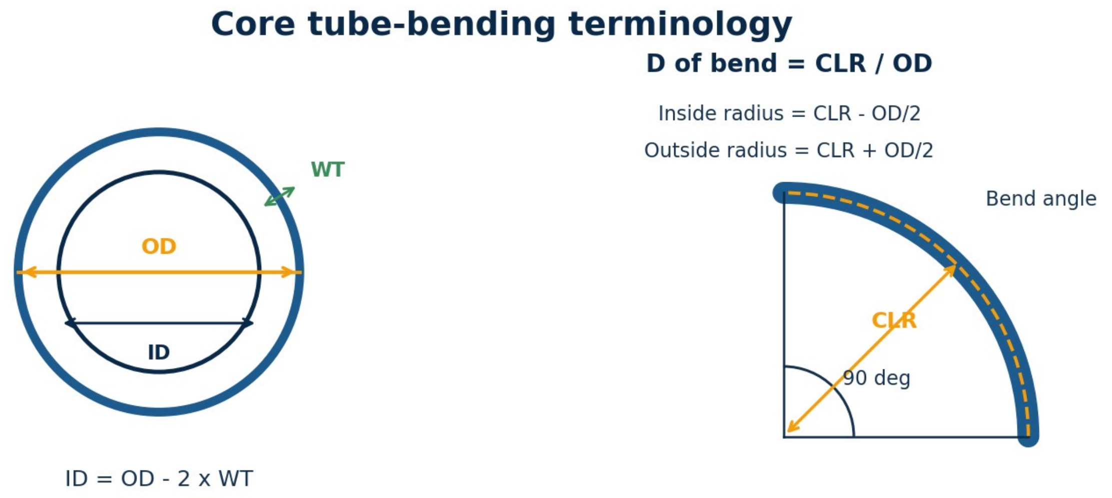
KINGSFORM METALWORKS

ENGINEERING TOOLKIT

TUBE FABRICATION DESIGN GUIDE

Design rules for bend geometry, tooling access, 3D tube layouts, end forming and inspection



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Practical engineering guidance - not a substitute for a released drawing, qualified process or applicable pressure / safety code.

01

Scope and how to use this guide

A design-for-manufacture reference for mechanical tube and profile parts.

This guide is written for product engineers, buyers, project managers and quality teams who need to specify bent tube parts clearly enough for quotation, tooling review and production. It covers round, square and rectangular mechanical tubing; the same geometry is often used for pipe, but pressure-containing or safety-critical piping must also follow the governing construction code and qualification requirements [14].

USE THIS GUIDE FOR: Non-pressure mechanical structures, handles, frames, guards, furniture, fitness equipment, agricultural equipment, material-handling products and fabricated assemblies.

DO NOT USE IT ALONE FOR: Pressure piping, roll-over structures, lifting devices, life-safety products or fatigue-critical systems. These applications require code- and load-specific engineering.

Design input package

- Tube material specification, grade, condition / temper, OD or section size, wall thickness and weld-seam requirement.
- 3D model plus a controlled 2D drawing with functional datums, bend radii, bend angles, rotations and end conditions.
- Target quantity, annual volume, cosmetic class, surface finish, welding and downstream assembly requirements.
- Inspection requirements for endpoint position, overall envelope, bend angle, rotation, ovality, wall thinning and surface condition.

Contents

02

Tube terminology and design inputs

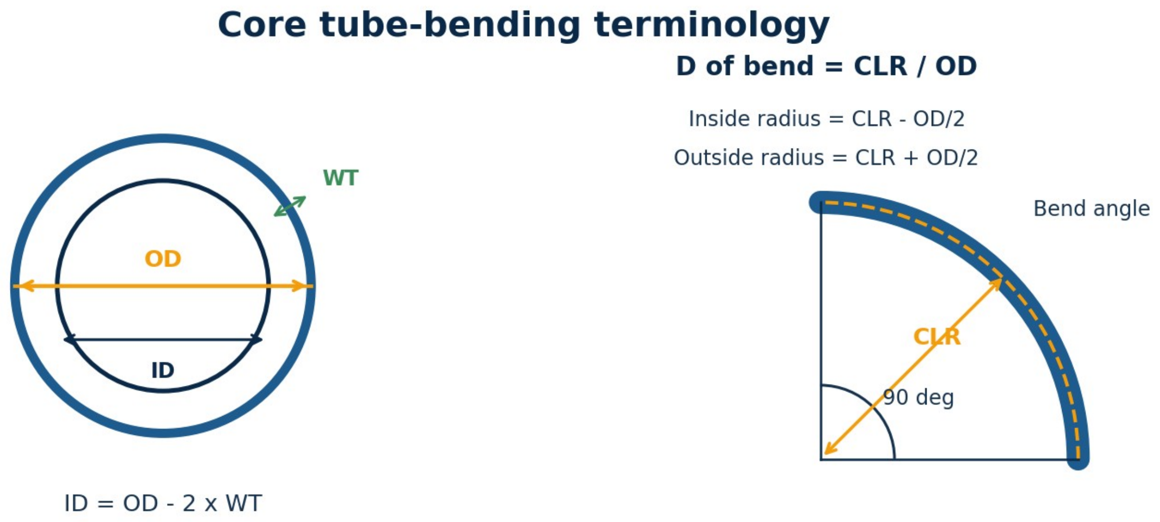

Figure 1. OD, ID, wall thickness and centerline bend geometry.

Outside diameter (OD), inside diameter (ID), wall thickness (WT) and centerline radius (CLR) must be unambiguous. The common bending ratios used by equipment suppliers are D of bend = CLR / OD and wall factor = OD / WT [2].

Term	Definition	Design consequence
OD / section size	Nominal outside size of round, square or rectangular tube.	Drives tooling groove, machine capacity and mating interfaces.
WT	Nominal wall thickness before forming.	Controls bend stability, weld penetration and thread / insert options.
CLR	Radius from bend center to tube centerline.	Defines bend die and developed arc length.
Tangent point	Where the straight transitions into the constant-radius bend.	Use tangent-to-tangent dimensions for clean bend data.
Bend plane	Plane in which a bend occurs.	Must be controlled for 3D parts and non-round profiles.
Rotation / clocking	Angular rotation about the tube axis between bends or end features.	A small rotation error can create a large endpoint error.

Order the raw tube by a complete material standard

Mechanical tube standards define product form, manufacturing route and tolerances; they do not automatically define a finished bent-part tolerance. Examples include ASTM A513/A513M-25 for ERW carbon and alloy steel mechanical tubing, ASTM A554-26 for welded stainless mechanical tubing, and ASTM B210/B210M-26 for drawn seamless aluminum-alloy tube [8-10]. Specify grade, condition, dimensional basis, surface condition and any supplementary tests required.

03

Choose the forming process before freezing the geometry

METHOD	BEST USE	ADVANTAGE	DESIGN LIMIT
Compression bending	Simple bends, moderate accuracy	Fast; lower tooling cost	More flattening; limited multi-bend control
Rotary draw bending	Tight radii, repeatable 2D/3D parts	Best control with mandrel / wiper	Requires dedicated tooling and clamp access
Roll bending	Large-radius sweeps and arcs	Smooth long radii	Less suitable for short tangent-to-tangent bends
Press / ram bending	Robust pipe, low precision	Simple equipment	High ovality and less dimensional control
Stretch bending	Large thin-wall sections	Good surface and smooth curvature	Specialized equipment and fixtures

Select the process before freezing bend radius, tangent length and tolerances.

Figure 2. Process selection overview.

The same nominal radius can have very different cost, deformation and tolerance outcomes depending on the bending process. Rotary draw bending is the normal starting point for controlled small-radius mechanical tube parts because the tube is wrapped around a fixed bend die and can be supported by a mandrel, wiper die and pressure-die assist [3-4].

Early supplier questions

1. Is the radius made by rotary draw bending, roll bending, compression bending or a dedicated forming die?
2. Is the required radius already covered by existing bend tooling, or does it require a new die set?
3. Can the machine grip the available straight length before and after each bend?
4. Does the part require mandrel support, a wiper die, pressure-die assist or carriage boost?
5. Can all bend radii and directions be produced in one setup, or will the part require re-chucking?

COST CONTROL: Standardize tube OD, wall thickness and CLR across a product family. Reusing bend dies and clamp tooling often saves more than optimizing a small amount of raw material.

04

Bend geometry, path length and cut-length planning

For a constant-radius bend, use the centerline radius to calculate the nominal arc length. This is the geometric length along the programmed tube centerline, not a guaranteed finished cut length.

Calculation	Formula	Example: OD 40 mm, CLR 80 mm, angle 90 deg
D of bend	CLR / OD	80 / 40 = 2.0D
Inside radius	CLR - OD / 2	80 - 20 = 60 mm
Outside radius	CLR + OD / 2	80 + 20 = 100 mm
Bend arc length	pi x CLR x angle / 180	pi x 80 x 90 / 180 = 125.66 mm
Outside path demand	OD / (2 x CLR)	40 / 160 = 25% longer than centerline path

IMPORTANT: The outside path-demand calculation is a geometric indicator, not the actual engineering strain. The neutral axis shifts, material flows, tooling pushes and wall thickness changes during bending.

Nominal developed length

A first-pass blank length is the sum of tangent straight lengths, centerline arc lengths and required end allowances. Production cut length must then include the real process: clamp scrap, end-form grip length, springback / stretch correction, trim allowance and any post-bend machining. For high-volume work, release the cut length only after a controlled first-article trial.

Input	Recommended drawing treatment
Straight length	Dimension tangent-to-tangent or endpoint-to-tangent; avoid ambiguous outside-apex dimensions.
Bend angle	State nominal angle and tolerance; distinguish machine command from released part angle.
Multiple radii	Identify each CLR and where the radius changes.
End trim	Define finished endpoint datums after all forming and welding.

05

Screen bend difficulty with D of bend and wall factor

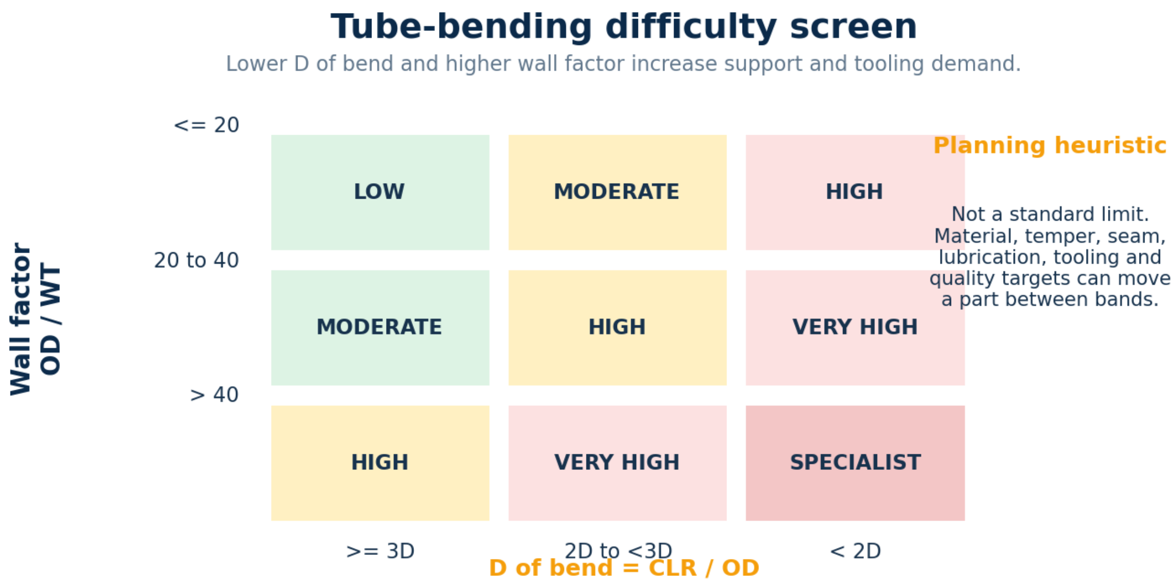

Figure 3. Planning heuristic. Confirm the actual limit with the selected material, machine and tooling.

A smaller CLR relative to OD increases the path-length difference between the inside and outside of the bend. A thinner wall relative to OD provides less resistance to flattening and wrinkling. Tooling suppliers therefore use D of bend and wall factor as core difficulty indicators [2,4].

Recommended design workflow

6. Start with the largest radius that meets the product envelope and appearance requirement.
7. Keep the wall thickness and material condition consistent with available tube supply.
8. Send high-difficulty parts to the bending supplier before design release.
9. Ask for a first-article report that includes ovality, minimum wall, bend angle, rotation and endpoint position.

1D GEOMETRY: At CLR = 1 x OD, the ideal outside arc path is 50% longer than the centerline arc. This explains why 1D bends need high elongation, material feed and strong tooling support; a simple free bend cannot achieve that geometry without significant deformation [15].

06

Control thinning, wrinkling, flattening and springback

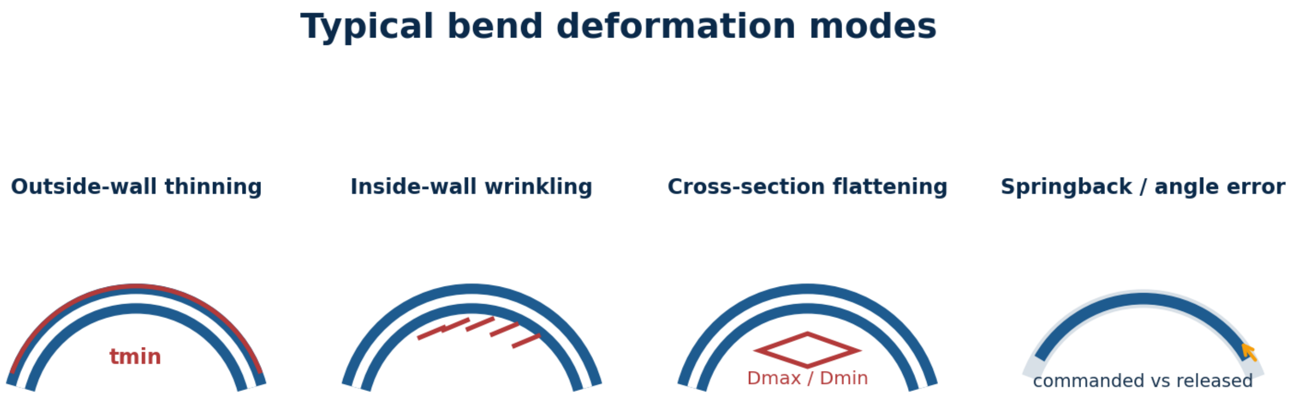

Figure 4. Common bend defects and dimensional shifts.

Risk	Primary mechanism	Design / process response
Outside-wall thinning	Outside fibers must follow a longer path; tube is stretched around the bend.	Increase CLR, use pressure-die assist / boost, increase wall, change temper, reduce friction.
Inside-wall wrinkling	Inside wall is compressed and buckles near the tangent.	Use wiper die, mandrel and correct pressure-die setup; increase CLR or wall thickness.
Flattening / ovality	Cross-section collapses under bending moment and tooling contact.	Use a mandrel, better groove support, larger CLR or thicker wall.
Springback	Elastic recovery opens the angle and changes radius / endpoint.	Overbend, calibrate by material lot, use controlled boost and inspect after release.
Surface marking	High tool pressure, dirty tooling or poor lubrication marks the surface.	Define cosmetic zones, polish tools, protect finish and control lubrication.

Do not specify one universal springback allowance

Springback changes with material grade, strength, temper, seam, CLR, wall factor, bend angle, tooling friction, lubrication and machine control. Use sample-based compensation for the actual production combination. When material lots change significantly, recheck critical endpoint and angle dimensions.

07

Tooling anatomy and support strategy

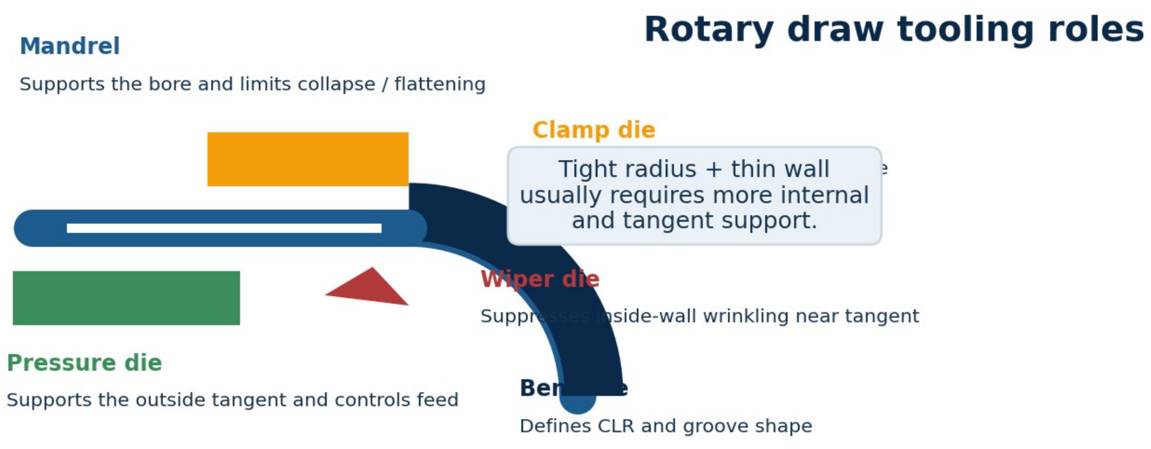

Figure 5. Rotary draw tooling functions.

The tooling package must support the tube through the tangent and bend. A ball mandrel is commonly used for difficult bends; the number and arrangement of balls depend on bend radius, OD, wall thickness and material [4]. A wiper die supports the compressed inside wall immediately behind the tangent, while the pressure die controls the outside tangent and can provide forward assist.

Part feature	Tooling consequence
Short straight before bend	May not provide enough clamp length. Dedicated clamp inserts, carriage push or compound tooling may be needed.
Hole, weld nut or bracket in clamp zone	Can prevent full clamping and can be crushed or marked.
Different radii in one part	May require multi-radius tooling and synchronized pressure-die movement [7].
Formed tube end before bending	May not pass through mandrel / collet or may reduce gripping area.
Cosmetic outer surface	Requires clean, polished tooling and defined acceptable witness marks.

TOOLING REVIEW TRIGGER: Any bend below 2D, wall factor above 40, straight between bends below 2D, preformed end, hole in the clamp zone or class-A finish should be reviewed with the bending supplier before release.

08

Straight lengths, clamp access and bend sequence

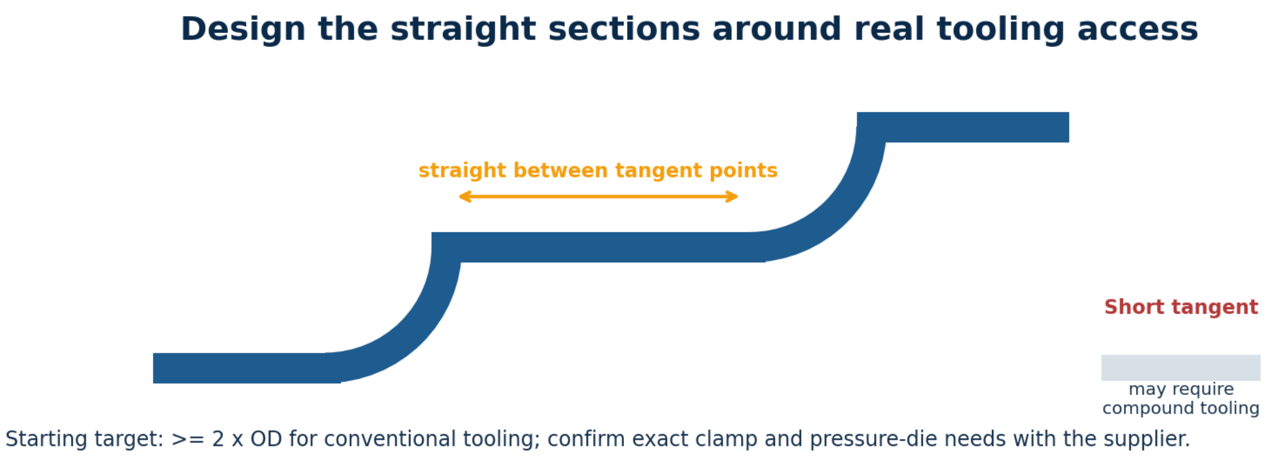

Figure 6. Starting point for straight length between bends.

Unison recommends at least 2 x tube diameter between bends as a cost-saving design target because standard tooling needs enough straight length to grip and support the tube [5]. Modern equipment can reduce clamp length to about 1D in some applications using dedicated control and tooling, but this must be confirmed rather than assumed [6].

Feature	Starting design target	When target cannot be met
Straight between tangent points	>= 2D	Use compound clamp / pressure tooling, multi-stack tooling or redesign the bend sequence.
Straight before first bend	Enough for clamp, collet and loading	Add sacrificial length and trim, or use a special collet / split clamp.
Straight after last bend	Enough for pressure die and end operation	Form the end after bending or add trim allowance.
Distance to welded bracket / boss	Keep outside all moving tools	Weld after bending or use a locating feature that does not enter the clamp zone.

Sequence matters

The first bend can block access to a later bend, collide with the machine, or leave no straight grip for the next operation. Supply the full 3D model and allow the supplier to simulate the bend sequence. For symmetrical two-bend parts, a twin-head process may reduce handling and improve symmetry; for complex 3D parts, rotary draw CNC bending is usually preferred.

09

Place holes, slots and attachments away from the bend zone

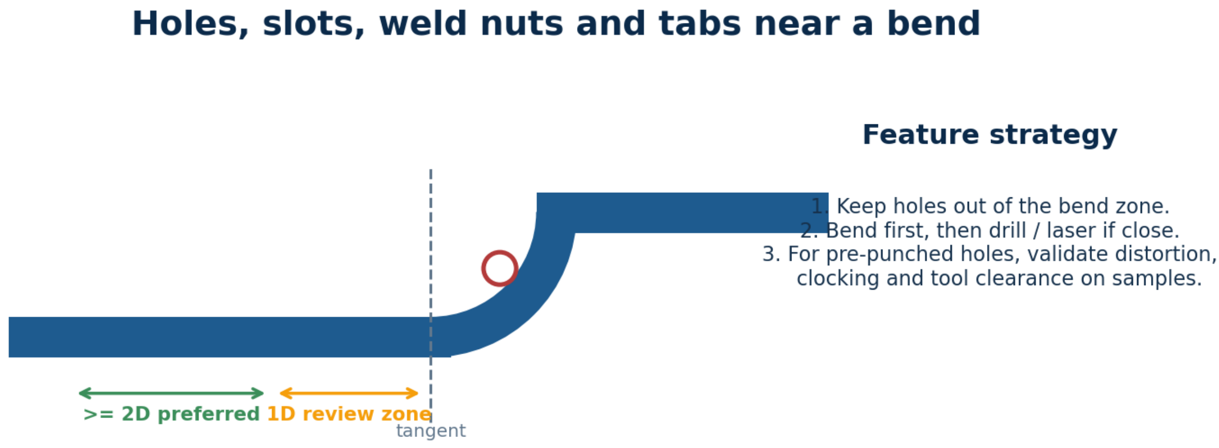

Figure 7. Internal planning zones for pre-punched features; not a universal standard.

Features close to the tangent can elongate, rotate, become oval, crack at the edge or interfere with the clamp / pressure die. There is no universal safe distance because the outcome depends on radius, wall factor, feature size, direction, material and tooling.

Distance from hole edge to tangent	Planning risk	Preferred action
>= 2 x OD	Lower risk for many conventional parts	Still check clamp and pressure-die contact.
1D to <2D	Review zone	Validate on first articles; consider bending before drilling.
< 1D or inside bend arc	High risk	Bend first, then drill / laser / machine, or use specialized internal support.

Feature-specific notes

- Slots parallel to the bend axis can open or neck; slots transverse to the bend can rotate and change width.
- Weld nuts and bosses require both tool clearance and a stable datum after bending. Install them after bending when practical.
- Pierced holes used as assembly datums should be produced after bending if their positional relationship to the final frame is critical.
- If a hole must be pre-punched, specify whether its size, position, ovality and edge cracking are controlled before or after bending.

10

Control multi-bend geometry, rotations and endpoint position

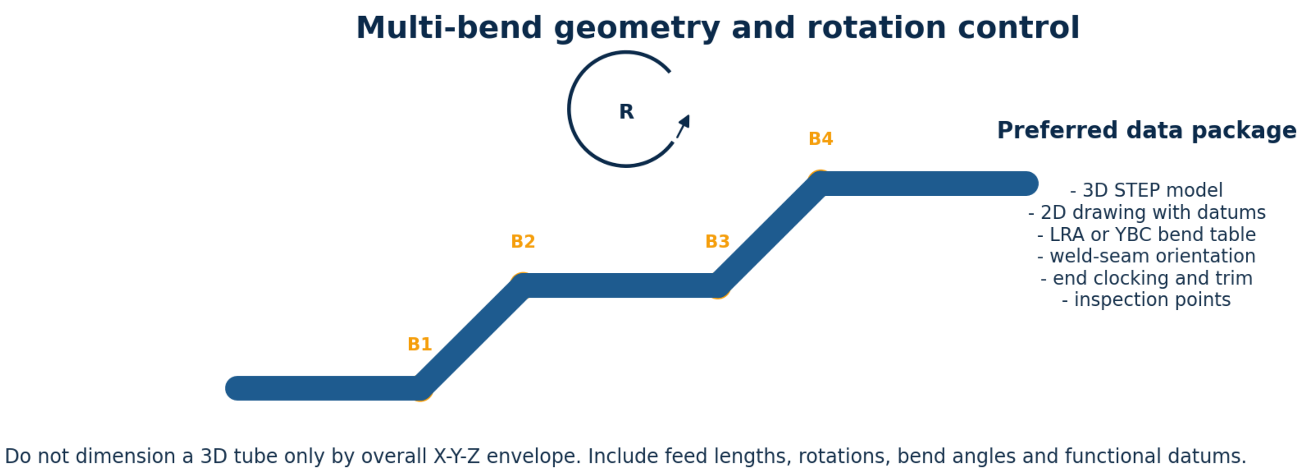

Figure 8. 3D tube definition requires feed, rotation and bend data.

CNC tube programs are commonly represented by feed length, rotation and bend angle data, often called LRA or YBC. Regardless of format, the drawing must establish the functional coordinate system and the intended relationship between ends, bends and mounting features.

Control	Recommended definition
Bend sequence	Identify B1, B2, B3... and supply the 3D model used to generate the bend data.
Rotation	Dimension between bend planes or provide a controlled bend table. Avoid only using a pictorial isometric view.
Endpoint position	Use basic dimensions and profile / position controls from functional datums where appropriate.
End clocking	State the angular orientation of holes, flats, flares, brackets or cut faces.
Trim length	Define final endpoints after forming; distinguish rough blank ends from finished ends.

ERROR ACCUMULATION: A small rotation error early in a long 3D tube can create a large endpoint deviation. Inspect critical rotations and endpoint position in a functional fixture rather than relying only on individual bend-angle checks.

11

Design square and rectangular tube by bend orientation

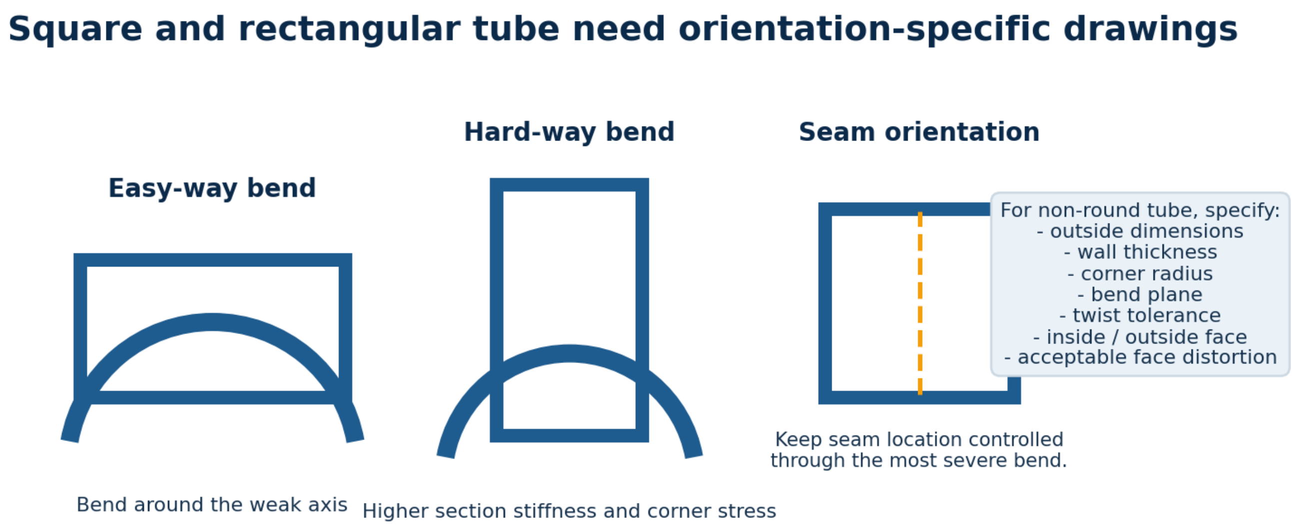

Figure 9. Non-round profiles require explicit bend orientation and seam control.

Round tube has continuous rotational symmetry; square and rectangular tube do not. Their face width, corner radius, seam location and bend orientation change the forming load and distortion pattern. ASTM A513/A513M and ASTM A554 cover round, square, rectangular and special shapes for applicable material families [8-9], but the finished bend acceptance still needs a project-specific definition.

Drawing requirement	Why it matters
Outside width x height x wall	Establishes the section and the easy / hard bending axis.
Corner radius and face flatness	Affects tooling groove contact and post-bend appearance.
Bend plane / inside face	Prevents a 90-degree orientation mistake.
Weld-seam orientation	Controls appearance and local bend behavior. For multi-plane bends, align the seam near the neutral axis of the most severe bend when practical [3].
Twist tolerance	Controls rotation of the section faces along the part.
Face concavity / convexity after bend	Defines what cross-section distortion is acceptable.

PROTOTYPE REQUIREMENT: Hard-way rectangular bends, thin walls, tight radii and cosmetic stainless sections should be validated with production-intent material and polished tooling before release.

12

End forming and secondary operations

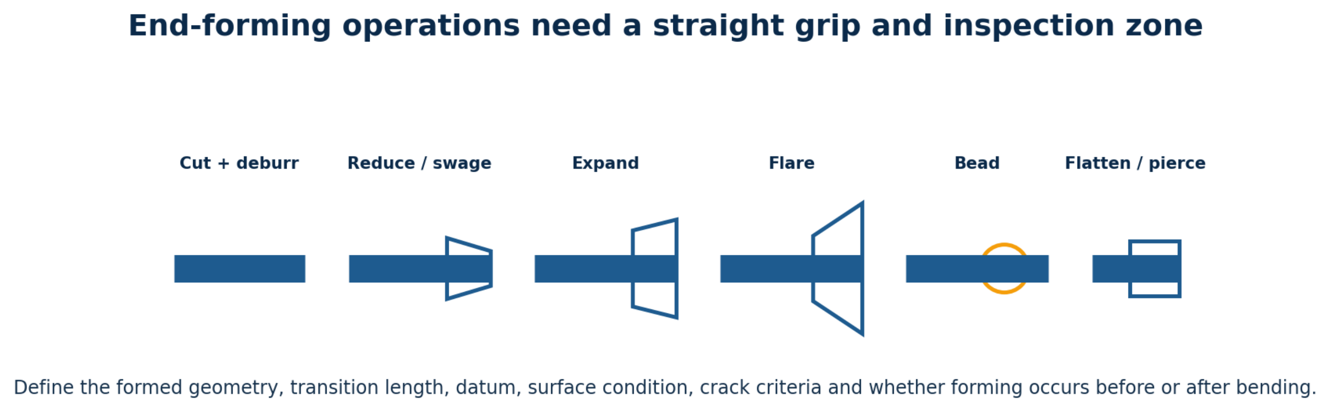

Figure 10. Common tube end-forming operations.

Operation	Critical drawing inputs	Typical risks
Cut / deburr / chamfer	Finished length, cut angle, edge break, burr direction.	Sharp edges, short length, swarf contamination.
Reduce / swage	Final OD / ID, transition length, concentricity and gauge requirement.	Wrinkles, splits, tool marks and non-concentricity.
Expand / bell	Expanded diameter, insertion depth, transition and split criteria.	Cracking, excessive thinning and taper.
Flare	Flare angle, outside diameter, seat condition and inspection gauge.	Edge cracks, uneven flare and surface damage.
Bead / groove	Bead diameter, width, location and height.	Local thinning, distortion and sealing mismatch.
Flatten / pierce	Flat width, thickness, hole size / position and edge condition.	Buckling, cracks, asymmetric flattening and springback.

Order of operations

Choose the sequence based on access and datum stability. End forms can block mandrel insertion or clamping; bending can distort a preformed end; welding can move a precisely formed endpoint. A robust sequence is often bend -> trim -> end form -> pierce / machine -> clean -> inspect, but high-volume parts may use integrated cut, bend and end-form cells. Transfluid notes that end-forming operations can require clamping lengths around 1 to 1.5 x diameter in some cases, which reinforces the need to reserve a grip zone [16].

13

Welded tube frames and assembly features

Bent-tube geometry and welded-frame geometry must be designed together. Welding can correct a small gap, but it should not be used to force a poorly controlled tube into position. Design the tube, joint preparation, fixture datums, weld access and distortion strategy as a system.

Design topic	Recommended practice
Joint type	Use cope / fishmouth joints, sleeves, tabs, laser-cut slots or formed saddles that locate repeatably.
Gap control	Define acceptable fit-up gap and where the gap is measured. Avoid a joint that relies on large weld metal to bridge geometry.
Fixture datum	Locate the frame from stable mounting surfaces and functional holes, not from a springy free tube end.
Weld access	Provide torch angle, electrode / wire access and room for clamps.
Heat balance	Use symmetrical joints, balanced weld length, sequence and intermittent welds when structurally acceptable.
Post-weld features	Machine or drill critical interfaces after welding when weld movement would otherwise exceed tolerance.
Drain / vent holes	Provide paths for pretreatment, coating, galvanizing or trapped moisture where the finish process requires them.

FRAME TOLERANCE: Do not apply a tight tolerance to every tube bend and then add an equally tight welded-frame envelope. Allocate tolerance by function and inspect the final assembly from the functional datums.

Cost-effective locating features

- Self-locating tabs and slots for clocking.
- Laser-cut witness notches for rotation and bracket position.
- Hard stops at finished ends rather than measuring every intermediate bend.
- Dedicated gauge pins for mounting holes and mating interfaces.

14

Drawing, datum and tolerance strategy

A tube drawing should communicate function, not duplicate every dimension from the 3D model. ASME Y14.5-2018 (R2024) and ISO GPS standards such as ISO 1101:2017 and ISO 5459:2024 provide the formal language for geometrical tolerancing and datum systems [11-13]. Use the standard specified by the customer and do not mix rule sets without a note.

Control method	Use it for	Avoid
Overall linear dimensions	Simple envelope, packaging and clearance.	Using only overall X-Y-Z dimensions for a 3D part.
Basic dimensions + profile	Controlling the tube centerline / outer surface relative to datums.	Adding separate plus/minus tolerances that conflict with profile.
Position of end features	Holes, tabs, brackets and interfaces relative to mounting datums.	Using the raw tube seam or cut end as a datum without functional reason.
Angular / clocking tolerance	Bend planes, end flats and attached features.	Leaving bend-plane direction implicit.
Local bend checks	Angle, CLR, ovality and minimum wall where function requires them.	Specifying impossible exact radius and zero flattening.

Minimum drawing information

- Material standard, grade, condition, section size, wall and weld-seam requirement.
- Finished part number, revision, units, projection method and governing tolerancing standard.
- CLR, bend angles, bend rotations / planes and final endpoint definitions.
- Functional datums, profile or position controls, critical characteristics and inspection method.
- End-form geometry, trim, burr / edge condition, welding, finish and marking requirements.

15

Inspection and acceptance planning

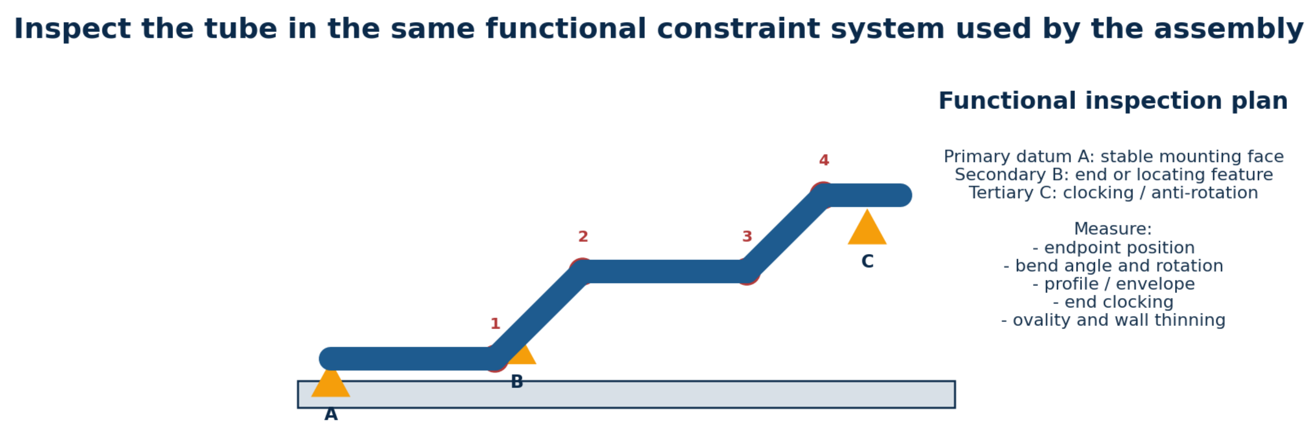

Figure 11. Datum-based functional inspection fixture.

Characteristic	Practical measurement	Project-specific acceptance
Bend angle	Angle fixture, arm measurement, CMM or optical system.	Nominal and tolerance after springback.
Rotation / clocking	Fixture clock, digital inclinometer, CMM or scan.	Angular tolerance between bend planes / end features.
Endpoint position	Checking fixture, CMM or scan from functional datums.	Position / profile or coordinate limits.
Ovality	Measure Dmax and Dmin at specified section.	Ovality % = (Dmax - Dmin) / Dnom x 100.
Wall thinning	Ultrasonic or sectioned sample at the outside of bend.	Thinning % = (t0 - tmin) / t0 x 100.
Wrinkling / flattening	Visual master, contour gauge, scan or dimensional section.	Amplitude / section limits and cosmetic class.
Surface condition	Controlled lighting and approved sample.	Tool marks, scratches, cracks, coating damage.

ISO 8491:1998 specifies a full-section bend test for circular metallic tubes and remains published after confirmation in 2020 [1]. It is a material ductility test, not a finished-part tolerance standard. Finished bend acceptance must come from the drawing, specification, qualified process or governing product code.

PRESSURE SERVICE: For a pressure-containing tube or pipe, use the applicable piping code and product standard for design, fabrication, examination and testing. ASME B31.3, for example, covers process piping materials, design, fabrication, assembly, inspection and testing [14].

Tube fabrication design review checklist

No.	Review item	No.	Review item
1	Material - Material standard, grade and condition / temper are stated.	14	Features - Critical holes are made after bending where appropriate.
2	Material - OD or section size, wall thickness and corner radius are stated.	15	Features - End-form sequence and grip length are defined.
3	Material - Welded / seamless route and seam-orientation requirement are stated.	16	Non-round - Easy / hard-way orientation and section twist are controlled.
4	Geometry - Every bend has a CLR, angle and bend-plane definition.	17	Welding - Joint preparation, fit-up gap, access and fixture datums are defined.
5	Geometry - 3D model and 2D drawing use the same revision and units.	18	Welding - Post-weld machining / drilling is used for critical interfaces where needed.
6	Geometry - Tangent points or bend table are unambiguous.	19	Tolerance - Functional datums and governing GD&T standard are identified.
7	Geometry - Final endpoints and trim allowances are distinguished.	20	Tolerance - Tolerance stack is allocated across bending, welding and assembly.
8	Difficulty - D of bend and wall factor have been reviewed.	21	Inspection - Bend angle, rotation and endpoint checks are defined.
9	Difficulty - Tight bends and thin walls have supplier feasibility approval.	22	Inspection - Ovality, minimum wall and surface criteria are defined where needed.
10	Tooling - Straight length before, between and after bends is sufficient.	23	Inspection - First-article quantity and reporting requirements are stated.
11	Tooling - Holes, weld nuts, brackets and end forms do not enter tool zones.	24	Finish - Cosmetic zones, tool-mark limits, cleaning and coating requirements are stated.
12	Tooling - Multiple radii / directions are compatible with the intended machine.	25	Commercial - Annual volume, prototype quantity and tooling ownership are clear.
13	Features - Hole and slot distortion near bends has been assessed.		

RELEASE GATE: Do not release the design until all high-risk items have a named owner, evidence and closure date.

17

Standards, technical sources and RFQ handoff

The sources below were checked when this guide was released. Verify the edition required by the contract before applying any standard. Public summaries do not replace a controlled copy of the full standard.

[1] ISO 8491:1998. Metallic materials - Tube (in full section) - Bend test. Published; last reviewed and confirmed in 2020. Official / source page

[2] Unison Ltd - Tube Bending Formulas and Guides. Definitions for D of bend, wall factor, ID, inside radius and outside radius. Official / source page

[3] Unison Ltd - Principles of Rotary Draw Bending. Process principles and weld-seam orientation for multi-plane bends. Official / source page

[4] Unison Ltd - Mandrels: the key to challenging tube bending. Mandrel selection based on D factor and wall factor. Official / source page

[5] Unison Ltd - How clever tube and pipe design can save money. Design recommendation of at least 2D distance between bends. Official / source page

[6] Unison Ltd - Control Features: Carriage Push. Example of clamp length approaching 1D with suitable control and tooling. Official / source page

[7] Unison Ltd - Multi-stack and multi-radius bending. Tooling implications for close bends and multiple radii. Official / source page

[8] ASTM A513/A513M-25. ERW carbon and alloy steel mechanical tubing in round, square, rectangular and special shapes. Official / source page

[9] ASTM A554-26. Welded stainless steel mechanical tubing. Official / source page

[10] ASTM B210/B210M-26. Aluminum and aluminum-alloy drawn seamless tubes. Official / source page

[11] ASME Y14.5-2018 (R2024). Dimensioning and tolerancing / GD&T. Official / source page

[12] ISO 1101:2017. Geometrical tolerancing - form, orientation, location and run-out. Official / source page

[13] ISO 5459:2024. Datums and datum systems. Official / source page

[14] ASME B31.3. Process piping requirements for materials, design, fabrication, assembly, inspection and testing. Official / source page

[15] Unison Ltd - The Powered Follower. Geometric explanation of material demand in a 1D bend. Official / source page

[16] transfluid - FLARELINE end-forming systems. Example clamping-length range for tube end-forming applications. Official / source page

RFQ HANDOFF: Submit the 3D model, controlled 2D drawing, tube material specification, bend table or clear bend callouts, annual quantity, cosmetic requirements, inspection plan and expected packaging. Use KFR-001 RFQ Template and KFR-002 Drawing Checklist to keep the package complete.

Engineering resources: www.kingsformmetalworks.com/resources