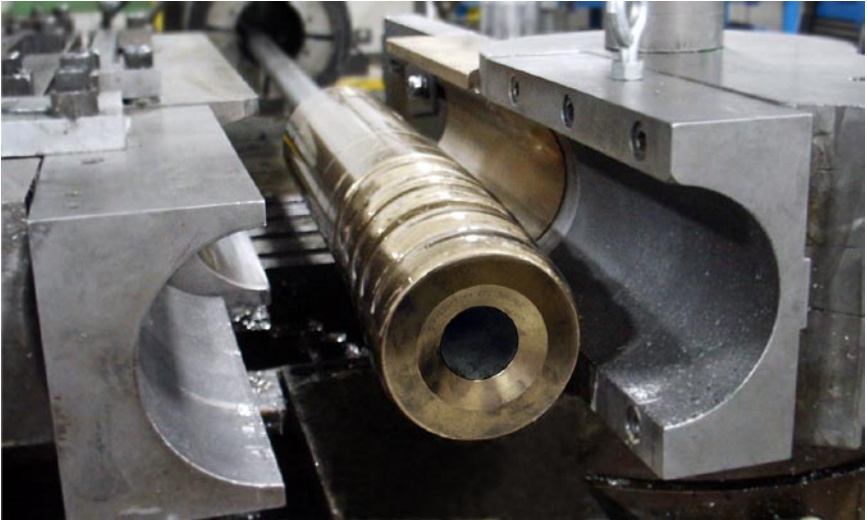# The Rotary-Draw
Tube-Bending Guide

Four Steps to Improved Bending

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The Tools Make The Bend

Even though we are in the age of computer-numerically controlled (CNC) machinery, the old bromide "the tools make the bend" is truer today than ever before. As applications have become more extreme in draw-bending, the design, set-up, and maintenance of tools has returned to central importance.

Our guide explains the principles of the set-up of tube-bending tools on a rotary-draw tube-bending machine.   We describe four simple steps for setting up a complete set of tools on a machine, which if executed precisely and in the correct order, will maximize bend quality, tool life, and process control.

Modern features on tube-bending machines, especially pressure-die assist, have permitted many tube-bending machine operators to rely more upon manipulating machine controls to obtain adequate results than upon a precise, systematic tool set-up.

Many optional controls on CNC tube-bending machines, such as variable assist pressure, circumferential boost, and in-cycle mandrel retraction, were created to make the most difficult applications practical. However, they are instead frequently used to push material about at the point of bend to overcome the defects of a poor set-up on routine applications.

This over-reliance on the machine's controls "squeezes" the tube into the desired shape through excessive use of radial force from the pressure die at the point of bend. Because this approach works against the axial tension on the tube that is natural to the rotary-draw process, high machine-actuated pressures must be used to force the part into shape.

Use of high pressure at the point of bend often forces the machine operator to trade off tool life or process control in order to achieve acceptable bend quality. A four-step set-up procedure that combines a forward mandrel position with lower machine pressures solves these problems.

For further assistance, phone us toll-free 800-284-8823 or visit our website, www.bendtooling.com

The Four-Step Set-up

It is not necessary to sacrifice longer tool life or improved process control for better bend quality. All three of these objectives can be optimized – right now. Most tube-bending applications can be immediately "de-pressurized" with existing tool sets through a precise, back-to-basics, four-step set-up procedure. This set-up is known as "Forward Mandrel, Low Pressure".

The purpose of this procedure is to precisely position on the critical working surfaces of your tools relative to the point of bend so that under minimum pressure they will exploit the natural axial flow of the tubing material and guide it into the desired shape.

The four steps in a "Forward Mandrel, Low Pressure" set-up are:

1. **Mandrel nose placement**
2. **Direct pressure die setting**
3. **Wiper tip rake**
4. **Pressure die assist setting**

The trick to successfully implementing the four-step set-up is understanding that only one aspect of bend quality can be addressed at each step.

Accurate placement of the mandrel nose ensures a stable round cross-section throughout the arc of the bend. A correct direct (or radial) pressure setting of the pressure-die stops the buckling of the inside radius. A wiper tip properly raked from the line of tangency prevents the wrinkle or series of small wrinkles that can form at the terminal end of the inside radius. And finally a balanced pressure-die assist setting will push out the outside radius sufficiently to mitigate flattening and to eliminate any terminal hump.

Not all draw-bending applications require a mandrel or a wiper or the use of pressure die assist (*refer to the mandrel-wiper selection chart on the inside back cover*). But knowing the limits of what can be accomplished at each point of the "Forward Mandrel, Low Pressure" set-up will help you to troubleshoot problems more accurately and quickly – and perhaps determine the need for one of these things if it is absent.

Furthermore, applying these steps in sequence will help overcome the common troubleshooting obstacle of one tool masking the failure of another – for example, excessive direct pressure die pressure covering up an improperly placed mandrel nose. The following descriptions of each step will clarify these troubleshooting issues.

Step #1: Mandrel Nose Placement
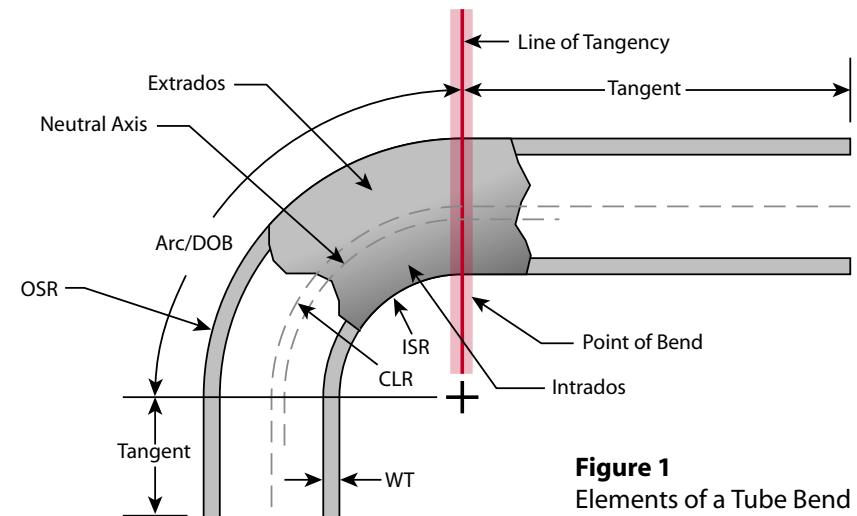
Figure 1
Elements of a Tube Bend

[See the "Terminology" section at the end of the guide for an explanation of the terms used in Figure #1. For further information on tube bending terms, go to our Bend Tooling Encyclopedia™ at www.bendtooling.com/encyclopedia.htm]

The mandrel is the central tool in the draw-bending set-up. It is your primary means of controlling the flow of tubing material at the point of bend. To understand the best placement of the mandrel nose it is useful to understand the difference between the line of tangency and the point of bend.

The line of tangency is a theoretical plane fixed in space. It is perpendicular to the plane of bend and divides the bend arc from the tangent. On the other hand, the point of bend is an indefinite region surrounding the line of tangency in which the tubing material is in a plastic state [Figure #1].

In this region the tube wall will thicken along the inside radius (intrados) and will thin along the outside radius (extrados) as the clamps draw the tube around the bend die. The purpose of the mandrel nose is to cover this region of flowing material and ensure a consistently round cross-section by mitigating the simultaneous compression and stretching of the tube wall.
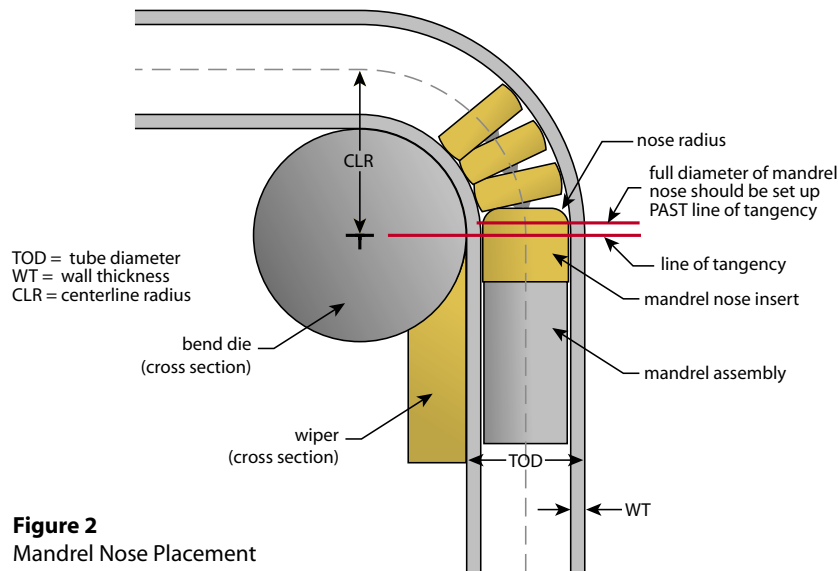
Figure 2
Mandrel Nose Placement

Because the point of bend extends past the line of tangency, so too must the mandrel nose to support it [Figure #2]. If it does not, then the compression and stretching of the tube wall is uncontrolled. This results in buckling and excessive flattening.

While more direct pressure-die (*i.e. radial*) pressure can often remedy the buckling along the inside radius, it will also exacerbate the flattening of the outside radius because of the additional drag it causes on the outside radius. Therefore, the mandrel nose placement past the line of tangency is critical, because it then can both eliminate buckling and minimize flattening.

Commonsense informs us that there is a limit to how deep the mandrel nose can be placed past the line of tangency into the bend. At some point the outside line of the mandrel nose will intersect the outside radius of the tube bend and force the tubing material to form over the contour of the nose and perhaps the balls. What intuition does not tell us is that this point is relatively deep into the bend and that, in most instances, tube-bending machine operators are not using the mandrel nose aggressively enough.

Several factors come into play in calculating how deep past the line of tangency the mandrel nose can be placed:

- **Tube diameter (d)**
- **Wall thickness (t)**
- **Centerline radius (r)**
- **Mandrel nose diameter (m)**
- **Mandrel nose radius (n)**

Using the Pythagorean Theorem you can calculate this maximum depth (b):

$$b = \sqrt{[\,r + (d/2) - t\,]^2 - [\,r + (m/2)\,]^2} + n$$

For instance, if the tube bend is a 2-inch tube diameter x .049-inch wall thickness x 4-inch centerline radius made with a standard diameter mandrel, then the maximum depth is more than 5/8 of an inch. Usually, a placement somewhere between one-half and two-thirds of the maximum is best. The less rigid the material the deeper the placement must be. This executes the "Forward Mandrel" principle of this set-up procedure. After this first step, you should have a bend that has a consistent cross-section throughout most of the arc. The most serious problem you might have is buckling throughout the inside radius.

If your mandrel nose is stable at the proper depth past the line of tangency and its diameter is not undersized for the application, then go onto the next step to determine the correct direct pressure-die setting. It is important to ensure that your mandrel nose is not undersized for the bend you want to make. There is a practical limit to how small a mandrel nose diameter can be and still be effective.

A properly sized mandrel nose is critical to mitigating flattening on the outside radius of the bend and buckling on the inside radius. The formula for a standard nose diameter (m) is:

$$m = d - (t \times 2.21)$$

If ease of loading is an important consideration, then the standard diameter (m) can be reduced by .005" for every inch of tube diameter (d). But if your mandrel nose diameter is substantially smaller than this, deeper placement of it past the line of tangency will not sufficiently compensate for its undersized condition. Buckling and flattening will occur.

If you have other problems such as terminal wrinkles on the inside radius or a terminal hump on the outside radius, continue on. These problems will be fixed later in the set-up.

Step #2: Direct Pressure Die Setting

In this next step you will execute the "Low Pressure" principle. If you have set the mandrel nose sufficiently forward into the bend so that it does most of the work in controlling the shape of the tube, then the only work the pressure-die needs to do is to apply enough pressure so the tube does not pull away from the bend die during the bend. (If it does pull away, then the inside radius will buckle into the gap created.) Intuition suggests that not much pressure is needed to do this job.

The pressure-die applies a radial force upon the tube at the point of bend. Because this radial force is perpendicular to the natural axial flow of material in the draw-bending process, drag results.

Too much drag and you will have terminal humps and excessive flattening of the outside radius. Too much drag is usually the culprit when the tube slips from the clamp dies. Your objective is to eliminate as much drag as possible by determining the lowest direct (radial) pressure needed to prevent buckling. Generally the more rigid the cross-section of the tube, the more direct pressure is needed to hold it against the pressure-die.

Most mild steel, stainless steel, aluminum, and copper round tube applications 3 inches and under in diameter will require relatively low direct pressure to accomplish this (*the actual setting varies with make and model of the tube-bending machine*).

Square and rectangular tubes (especially if bent the "hard-way") will require higher pressures. So will copper-nickel, super-alloy, and some nickel-stainless tubes. Unfortunately there is no simple formula for calculating the optimum setting because such factors as tube shape and size, wall thickness, centerline radius, degree of bend, and material rigidity must all be taken into account. An additional problem is that the pressure reading from the machine may not reflect what is actually applied to the tube.

However, some time spent here on trial-and-error will yield benefits. A rule of thumb can help to establish a good starting point. Assuming a typical 3-inch capacity machine, set the direct pressure at 30-50 KSI (*1,000 pounds per square inch*) for the softest round tubular material such as soft aluminum, soft copper, and low-carbon hydroformable steel. Increase this 50-100 KSI for high-carbon steels, stainless steels, hard aluminum, and hard copper. For the most rigid materials, such as titanium, nickel stainless, superalloys like Iconel, and non-round tubing of any material, a setting of 100-200 KSI is typical.

If continuous wrinkling or a buckle forms on the inside radius, increase the direct pressure setting in increments of 10 to 20 KSI until this problem disappears. If there is no deformation on the inside radius, consider

dropping the direct pressure. Once you determine the minimum direct pressure your application requires, you can rely upon this value for future set-ups of the same application and as a guideline to other applications.

At the end of this step you will have combined the "Forward Mandrel" and "Low Pressure" concepts behind this set-up to produce an acceptable bend. Some imperfections may still persist, such as a terminal inside radius wrinkle or terminal outside radius hump. These can be fixed by the last two steps of the set-up procedure.

Step #3: Wiper Tip Rake

The wiper's job is to prevent a wrinkle from forming at the end of the bend. Check whether or not there is a wrinkle at the terminal end of an otherwise smooth inside radius. If not, you do not need a wiper, and this step is completed. If so, the wiper tip needs to be positioned for optimal tool life.
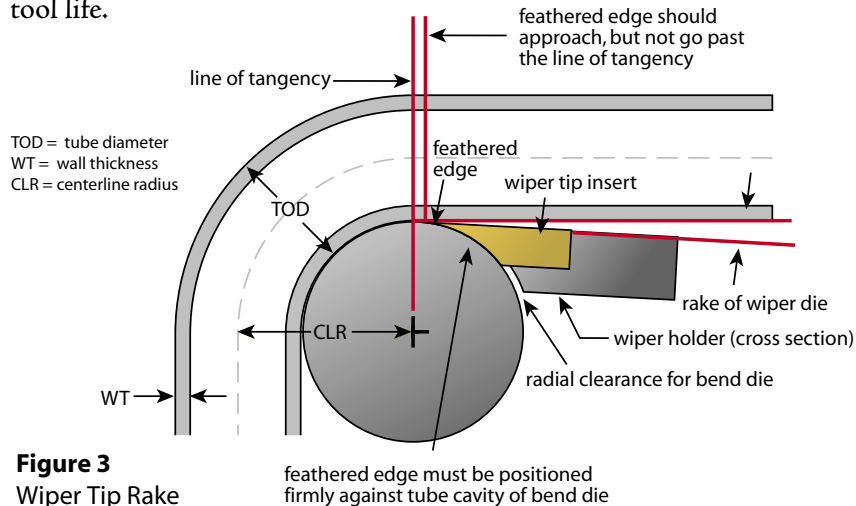
Figure 3
Wiper Tip Rake

The wiper fills the gap behind the line of tangency between the inside line of the tube and the curve of the bend die cavity [Figure 3]. If the tube wall is not sufficiently rigid it will bulge outward to fill this gap. With enough direct pressure-die pressure this bulge will flatten out between the bend die cavity and the mandrel nose as the tube is drawn through the line of tangency. But at the terminus of the bend the bulge

is not drawn through and flattened, and it can then form a wrinkle, or small series of wrinkles, if the bulge extends far enough to exceed the elasticity of the tubing material.

Properly set, the tip of the wiper will catch the top of this terminal bulge before it sets into that wrinkle. Note that because all tubing materials have some elasticity, the bulge will to a certain extent flatten itself out once pressure is relieved from the point of bend.

Therefore, it is not necessary for the wiper tip to contain the entire height of the terminal bulge. The wiper tip needs to obstruct only that marginal bulging which exceeds the material's elasticity and would set the entire bulge into a permanent wrinkle.

This is why a wiper can be raked away from the line of tangency. The value of raking the wiper is that doing so extends its life. The key to this step in the "Forward Mandrel, Low Pressure" set-up is finding the natural resting position of the wiper at zero rake and then determining the maximum rake that can be set for the application.

To do this, hold a straightedge at the bottom of the grip section of the bend die cavity. With the wiper loosely mounted on the wiper post, bring in the wiper so that the bottom of its cavity also lines up with the straightedge. The wiper is now at zero rake.

To find its natural resting position, gently slide the wiper along the straightedge towards the line of tangency until resistance is met. Check if the feathered edge of the wiper tip is in complete contact with the bend die cavity. If so, you have found the natural fit. If not, apply slightly more force until the feathered edge is securely backed by the bend die cavity. If you must use considerable force to find a "fit", most likely the wiper is improperly cut or you are trying to get the tip too close to the line of tangency. The latter is a common problem because to the eye it looks better when the wiper is at the line of tangency; however, most wipers are not cut to permit such a setting, nor is it necessary if the purpose of the wiper is limited to containing the terminal bulge.

Once you have found the natural zero rake position, rake the wiper by rotating the tip along the bend die cavity away from the line of tangency. You can increase rake in this manner so long as the terminal bulge does not set into a wrinkle (*for high-pressure tube-bending applications - see the mandrel-wiper selection chart for reference - the wiper usually must be left at zero rake*). Once you have set the rake, you can measure the linear distance along the bend die cavity from the wiper tip to the line of tangency. Provided that replacement wiper tips are of the same design and manufacture, you can short-cut this step in the set-up by setting a new wiper at this distance.

Step #4: Pressure Die Assist Setting

Like the wiper, pressure die assist is not necessary if there are no remaining flaws for it to fix. In this case, if there is no terminal hump on the outside radius and the flattening is acceptable, you do not need pressure die assist. Turn it off or set it to a neutral pressure (depending upon your machine), and your set-up is complete. Otherwise start from a neutral pressure setting and increase the assist until the flaws disappear.

Keep in mind that many newer CNC tube-bending machine have both "assist" pressure and "boost" pressure. The term "boost" generally means a type of axial pressure applied during the bend to the entire circumference of the tube by means of clamps behind the pressure die. Using this type of pressure forces material through the line of tangency to feed both the intrados and the extrados. Assist, on the other hand, feeds material only into the extrados which is useful in decreasing flattening and wall-thinning.

Trial and error with a limited range will determine the minimum pressure die assist setting to complete the "Forward Mandrel, Low Pressure" set-up. If a high or unstable setting results, it is necessary to re-examine the three preceeding steps, because the assist setting is masking or unable to overcome the problem.

Troubleshooting

One of the advantages of the four-step set-up procedure just described is that it facilitates troubleshooting. Most defects in a tube bend can be traced to the set-up, and most set-up defects correlate with problem in one of the four steps. Therefore, once you have identified the nature of the defect, you will have a specific set-up parameter you should examine first.

Mandrel Nose Problems:

- **Ovality (i.e., general deformation of the tube's cross-section) is excessive.** Check if the mandrel nose is undersized or not placed deep enough into the bend. If undersized, a temporary fix may be to advance it deeper into the bend. However, optimal bending will require a new mandrel made to the correct nose diameter.

- **The inside radius buckles.** Check if the mandrel nose is placed behind the line of tangency. If so, advance past tangency according to the directions on Pages 3 through 6.

- **The outside radius collapses.** Check if the mandrel nose is placed behind the line of tangency. Advance past the line of tangency according to the directions on Pages 3 through 6.

- **A hump or humps form on the outside radius.** This is usually not because the mandrel nose is too deep into the bend, but because there is excessive drag or insufficient assist from the pressure die. See below for details. However, if you do suspect the mandrel nose is the problem, check the depth of its placement and compare it to the formula on Page 5. If the mandrel nose placement is too deep according to this formula, then retract it.

- **Drag is excessive.** This is not a defect but an immediate cause of many defects. Too much direct pressure-die pressure is usually the culprit, however, an oversized mandrel nose can be the problem.

Check if the mandrel nose diameter is too large by using the formula on Page 6. If so, the mandrel will have to be replaced.

Direct Pressure Problems:

* **Continuous wrinkling of the inside radius.** If the entire arc of the inside radius is wrinkled, this indicates that the direct pressure-die pressure is too low. Use the guidelines on Pages 6 through 8 to determine the proper pressure.

  Note that this defect is distinct from a single hump or a small series of humps forming on the inside radius at the end of the bend. This type of wrinkling is associated with the wiper die. (See below.)

* **Excessive flattening of the outside radius.** A very common problem that results from too much direct pressure-die pressure. In effect, the pressure die is clamping on the tube at the point of bend causing the outside radius to stretch and flattening between the pressure die and the clamp die. Reduce the pressure according to the directions on Pages 6 through 8.

  If the mandrel nose is properly placed and the direct pressure is correct and flattening is still too much, then the assist pressure should be increased. (See below.)

Wiper Tip Problems:

* **A hump or humps form on the inside radius at the end of the bend.** As described on Pages 8 through 10, the role of the wiper is limited. These humps are the only problem the wiper is designed to solve, and these humps only occur if the wiper is not raked correctly or is worn out. Decreasing the rake will eliminate this probem. See Pages 8 through 10 for the best way to set the wiper tip rake.

Assist Pressure Problems:

* **Excessive flattening of the outside radius.** If excess direct pressure has been eliminated as a source of this defect (see above), then increase the assist pressure.

* **A hump or humps on the outside radius.** Respond to this in the same way as to excessive flattening if mandrel nose placement is correct.

* **Excessive wall thinning.** If ovality and flattening are under control, then increase the assist pressure.

Other Sources of Problems:

While the set-up is most often the source of a bending problem, other factors can cause trouble. If you have double-checked yourself and have not discovered the problem in the set-up, consider these possibilities:

* The machine is not applying pressure consistently.

* The machine is not lubricating the tooling properly.

* The tools are worn out.

* The working surfaces of the tools are mismatched or dimensionally incorrect for the bending application.

* The tubing material is undersized, oversized, or the wrong wall thickness.

* The tubing material is too hard or too soft.

No Longer A Black Art

Like many other types of metalforming, rotary-draw bending of tubing has often called a "black art" by its practitioners. This is because draw bending is a non-linear process, in which several – sometimes unmeasurable – variables come together to produce unpredictable results. However, this unpredictability is a matter of scale. Perhaps in the thousandths of an inch, even the very best bending machine operator cannot determine the precise outcome of a draw bending set-up. But in the realm of hundredths and tenths of an inch, draw-bending is indeed a predictable, repeatable process. In fact, far from being an art, draw bending is one of the most controllable metalforming processes today.

The means to this control is the four-step set-up procedure we just covered. It brings genuine process control over this black art. It provides an objective, measurable response to the variables present in every rotary draw-bending application.

Each application is a nexus of machine, tooling, material, and the operator. The operator controls how these elements are brought together and is, therefore, the biggest variable. The "Forward Mandrel, Low Pressure" four-step set-up is a precise, systematic, and repeatable method for the operator to combine these elements in the pursuit of better bend quality, longer tool life, and improved process control.

Rotary-draw tube-bending is no longer a black art with the four-step set-up.

Terminology
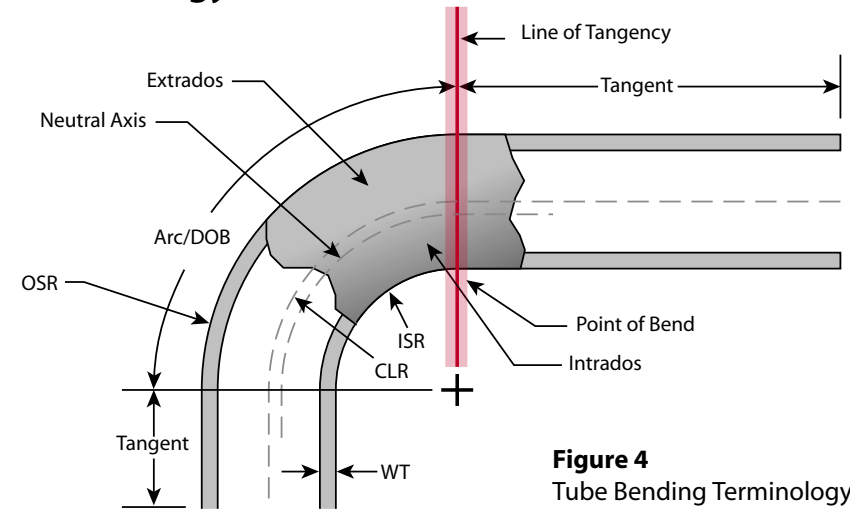
Figure 4
Tube Bending Terminology

Bend Specifications

TOD is tube outside diameter, usually measured in inches or millimeters. Sometimes the tube outside diameter is expressed in nominal, such as IPS for pipe. Only rarely is a tube diameter specified as an inside diameter. This is non-standard, leads to confusion, and should be avoided. Whatever units are used, TOD should be expressed in decimal, to three places in the case of inches.

WT is wall thickness. Inches and millimeters are common units, and again the precision of a decimal number to three places is warranted if inches are used; at least one place for millimeters. Frequently, the old Birmingham Wire Gage Standard is used to express WT; be sure to use the correct gage (there are several standards) when translating to decimal inches. When the TOD is expressed as an IPS nominal size, then the WT is expressed as a schedule number, which corresponds to a precise value in inches.

CLR is centerline radius and is the most common reference for bend radius. Again, inches and millimeters are the common units of measurement. Typically, fractional or two-place decimal inches are sufficiently precise. Sometimes the CLR is expressed as a multiple of the TOD, such as "1-D", "2-D", and so on. Note that if the TOD is expressed as an IPS nominal size and the CLR is expressed as a "D", it is a multiple of the nominal, not the actual tube diameter. Inside radius, abbreviated "ISR", is a common reference for specifying bend radius if the tubing is non-round. Outside radius is seldom used to define the bend radius.

DOB is degree of bend, often loosely referred to as the sweep of bend or depth of bend. This defines in decimal degrees (occasionally degrees and minutes) the arc of the bend. This is, of course, different from "plane of bend" or "orientation", a specification for multi-bend parts which defines in degrees where the plane of the current bend is located relative to the plane of the first bend.

In defining multi-bend parts, XYZ rectangular coordinates are used, from which bend data are developed. Bend data consist of tangent length, plane of bend, and degree of bend and defines the motion of the tube during the bending process.

Geometry

All bent parts consist of **arcs** and **tangents**. The arc is simply the bent portion of the tube, and the tangent the unbent portion.

Inside radius (ISR) and **outside radius (OSR)** are nominal references defining the extreme inner and outer limits of the tube arc. The centerline radius **(CLR)** is, of course, the average of these two.

Plane of bend is the plane defined by the inside and outside radiuses.

Line of tangency is actually a plane, perpendicular to the plane of bend, passing through the origin of the bend and the beginning point of the bend (in other words, it separates the arc of the bend from the tangent section). Before the line of tangency, the tube is straight. Past the line of tangency, it is bent. In draw bending, the line of tangency is fixed in space, through which the tube is drawn around the bend die as it rotates.

Regions

The regions of a bend are often confused with their related geometric terms. These regions, unlike the geometry defined above, are not precisely delineated because they described variable areas of common behavior during the bending process. For example, **point of bend vs. line of tangency.** The point of bend is the area of the tube on both sides of the line of tangency that becomes plastic and formable.

Neutral axis vs. centerline radius. It happens that the neutral axis is physically close to the centerline radius, but these terms are not synonymous. The neutral axis is a narrow region, lying inside of the centerline radius, separating the zone of compression from the zone of stretching. At the neutral axis the tube wall neither compresses nor stetches.

Intrados vs. inside radius. The intrados is the zone of compression, bounded by the inside radius and the neutral axis.

Extrados vs. outside radius. The extrados is the zone of stretching, bounded by the outside radius and the neutral axis.

CONVERSION CHARTS:

IPS Pipe System

Nominal Diameter	True Diameter		Schedule 5		Schedule 10		Schedule 40		Schedule 80		Schedule 160	
	inch	mm	inch	mm	inch	mm	inch	mm	inch	mm	inch	mm
1/8"	0.405	10.29			0.049	1.24	0.068	1.73	0.095	2.41		
1/4"	0.540	13.72			0.065	1.65	0.088	2.24	0.119	3.02		
3/8"	0.675	17.15			0.065	1.65	0.091	2.31	0.126	3.20		
1/2"	0.840	21.34	0.065	1.65	0.083	2.11	0.109	2.77	0.147	3.73	0.187	4.75
3/4"	1.050	26.67	0.065	1.65	0.083	2.11	0.113	2.87	0.154	3.91	0.218	5.54
1"	1.315	33.40	0.065	1.65	0.109	2.77	0.133	3.38	0.179	4.55	0.250	6.35
1-1/4"	1.660	42.16	0.065	1.65	0.109	2.77	0.140	3.56	0.191	4.85	0.250	6.35
1-1/2"	1.900	48.26	0.065	1.65	0.109	2.77	0.145	3.68	0.200	5.08	0.281	7.14
2"	2.375	60.33	0.065	1.65	0.109	2.77	0.154	3.91	0.218	5.54	0.343	8.71
2-1/2"	2.875	73.03	0.083	2.11	0.120	3.05	0.203	5.16	0.276	7.01	0.375	9.53
3"	3.500	88.90	0.083	2.11	0.120	3.05	0.216	5.49	0.300	7.62	0.437	11.10
3-1/2"	4.000	101.60	0.083	2.11	0.120	3.05	0.226	5.74	0.318	8.08		
4"	4.500	114.30	0.083	2.11	0.120	3.05	0.237	6.02	0.337	8.56	0.531	13.49
5"	5.563	141.30	0.109	2.77	0.134	3.40	0.258	6.55	0.375	9.53	0.625	15.88
6"	6.625	168.28	0.109	2.77	0.134	3.40	0.280	7.11	0.432	10.97	0.718	18.24

K-Type and L-Type Copper Pipe System

Nominal Diameter	True Diameter		K-Type WT		L-Type WT	
	inch	mm	inch	mm	inch	mm
1/4"	0.375	9.53	0.035	0.89	0.030	0.76
3/8"	0.500	12.70	0.049	1.24	0.035	0.89
1/2"	0.625	15.88	0.049	1.24	0.040	1.02
5/8"	0.750	19.05	0.049	1.24	0.042	1.07
3/4"	0.875	22.23	0.065	1.65	0.045	1.14
1"	1.125	28.58	0.065	1.65	0.050	1.27
1-1/4"	1.375	34.93	0.065	1.65	0.055	1.40
1-1/2"	1.625	41.28	0.072	1.83	0.060	1.52
2"	2.125	53.98	0.083	2.11	0.070	1.78
2-1/2"	2.625	66.68	0.095	2.41	0.080	2.03
3"	3.125	79.38	0.109	2.77	0.090	2.29
3-1/2"	3.625	92.08	0.120	3.05	0.100	2.54
4"	4.125	104.78	0.134	3.40	0.110	2.79
5"	5.125	130.18	0.160	4.06	0.125	3.18
6"	6.125	155.58	0.192	4.88	0.140	3.56

Birmingham Wire Gauge System

BWG #	inch	mm	BWG #	inch	mm	BWG #	inch	mm	BWG #	inch	mm	BWG #	inch	mm	BWG #	inch	mm	BWG #	inch	mm
5/0	0.500	12.70	2	0.284	7.21	8	0.165	4.19	14	0.083	2.11	20	0.035	0.89	26	0.018	0.46	32	0.009	0.23
4/0	0.454	11.53	3	0.259	6.58	9	0.148	3.76	15	0.072	1.83	21	0.032	0.81	27	0.016	0.41	33	0.008	0.20
3/0	0.425	10.80	4	0.238	6.05	10	0.134	3.40	16	0.065	1.65	22	0.028	0.71	28	0.014	0.36	34	0.007	0.18
2/0	0.380	9.65	5	0.220	5.59	11	0.120	3.05	17	0.058	1.47	23	0.025	0.64	29	0.013	0.33	35	0.005	0.13
0 or 1/0	0.340	8.64	6	0.203	5.16	12	0.109	2.77	18	0.049	1.24	24	0.022	0.56	30	0.012	0.30	36	0.004	0.10
1	0.300	7.62	7	0.180	4.57	13	0.095	2.41	19	0.042	1.07	25	0.020	0.51	31	0.010	0.25			

BEND TOOLING MANDREL AND WIPER SELECTION CHART™

Wall Factor (Tube Diameter / Wall Thickness)	"D" of Bend (Centerline Radius / Tube Diameter)											
	0.75	1	1.25	1.5	2	2.5	3	4	5	7	9	12
0	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN
5	R0N	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN
7	R1N	R0N	R0N	R0N	NNN	NNN	NNN	NNN	NNN	NNN	NNN	NNN
10	R1W	R1N	R1N	R1N	R0N	R0N	R0N	NNN	NNN	NNN	NNN	NNN
15	R2W	R1W	R1W	R1N	R1N	R1N	R1N	R0N	NNN	NNN	NNN	NNN
20	R2W	R2W	R2W	R1W	R1W	R1N	R1N	R0N	R0N	NNN	NNN	NNN
25	R3W	R2W	R2W	R2W	R1W	R1W	R1W	R1N	R0N	R0N	NNN	NNN
30	R3W	R3W	R3W	R2W	R2W	R2W	R1W	R1W	R1N	R0N	R0N	R0N
35	R3W	R3W	R3W	R3W	R2W	R2W	R2W	R2W	R1W	R0N	R0N	R0N
40	C4W	R3W	R3W	R3W	R3W	R2W	R2W	R2W	R2W	R1N	R0N	R0N
45	C4H	C4W	R3W	R3W	R3W	R3W	R2W	R2W	R2W	R1W	R0N	R0N
50	C4H	C4W	C4W	R3W	R3W	R3W	R3W	R3W	R3W	R2W	R1N	R0N
60	C4H	C4H	C4W	C4W	C4W	R3W	R3W	R3W	R3W	R2W	R1W	R0N
70	C5H	C4H	C4H	C4W	C4W	R3W	R3W	R3W	R3W	R3W	R2W	R1N
80	C5H	C5H	C5H	C4H	C4H	C4H	C4H	C4H	C4H	R3W	R2W	R1W
90	C5H	C5H	C5H	C5H	C5H	C4H	C4H	C4H	C4H	C4H	R3W	R2W
100	C6H	C5H	C5H	C5H	C5H	C5H	C5H	C4H	C4H	C4H	C4H	R3W
125	C6H	C6H	C6H	C5H	C5H	C5H	C5H	C5H	C5H	C4H	C4H	C4H
150	D7H	C6H	C6H	C6H	C6H	C6H	C6H	C5H	C5H	C5H	C4H	C4H
175	D8H	D7H	D7H	D7H	D7H	D7H	D7H	C6H	C6H	C5H	C5H	C5H
200	D9H	D9H	D9H	D9H	D8H	D8H	D8H	D7H	D7H	C6H	C6H	C6H

NNN   Zone 1: Mandrel bending optional.

R2W   Zone 2: Mandrel bending required; inserted tooling recommended.

C5H   Zone 3: Mandrel bending required; high-pressure tooling recommended.

1st character: "N" = no mandrel required, "R" = regular-pitch mandrel, "C" = close-pitch mandrel, "D" = double-close-pitch mandrel.
2nd character: "0" = plug mandrel, "1" through "9" = ball mandrel.
3rd character: "N" = no wiper required, "W" = standard inserted mandrel and wiper, "H" = high-pressure mandrel and wiper.

Notes:
[1] Recommendations based upon 180-degree bend of mild steel round tubing.
[2] Recommendations based upon "forward nose" set-up using link-type (as opposed to cable) mandrel.
[3] Regular-pitch mandrels may have either a small nose radius (for precision bending) or large nose radius (for high-production bending); for all other mandrels, the small nose radius is recommended.
[4] For stainless steel, titanium, copper-nickel, and "T6" aluminum tubing materials, adjust one column to the left for best recommendation; for nickel stainless and nickel alloys adjust two columns to the left.

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