SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR5378

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Reaffirmed 2013-01

Aircraft Tube Bending Methods, Techniques and Tooling

RATIONALE

AIR5378 has been reaffirmed to comply with the SAE five-year review policy.

1. SCOPE:

This SAE Aerospace Information Report (AIR) is intended to assist tube bending facilities dedicated to aerospace/aircraft applications. It describes in part the principles, methods, tool selection, and tool set-up requirements to achieve tube bends with aircraft quality.

2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AIR1388 Service Damage Limits for Aircraft Hydraulic Tubing

3. REQUIREMENTS:

3.1 Ovality and Wrinkle Considerations for Hydraulic Systems Tubing:

Ensure that ovality and wrinkle resulting from bending of the tube should not exceed the limits defined in Table 1 and Figure 1.

TABLE 1 - Allowable Ovality and Wrinkle for Hydraulic Tubing Bends

System Operating Pressure	Tube OD	Tube Material	Allowable Wrinkle Height (inches)	Allowable Ovality* (Percent of Nominal OD)
Liquid:	All Sizes	Stainless Steel	0.010	5
1000 to 3000 psi		Aluminum	0.010	5
(Including Return Lines)		3Al-2.5V Titanium	None Visible	3
Pneumatic and Oxygen: Pressure Above 1500 psi	All Sizes	Stainless Steel	0.010	5
Other Liquid Systems: Pressure Less Than 1000 psi	Less Than 1.0	Stainless Steel	0.040	10
		Aluminum Alloy & Copper	0.020	10
Pneumatic and Oxygen Systems: Pressure Less Than 1500 psi	1.0 or Over, Less Than 2.0	Stainless Steel	0.060	10
		Aluminum Alloy & Copper	0.030	10
	2.0 or Over, Less Than 3.0	Stainless Steel	0.050	5
		Aluminum Alloy & Copper	0.040	5
	3.0 or Over	Stainless Steel	0.100	5
		Aluminum Alloy & Copper	0.050	5

$$* \text{ Ovality} = \frac{\text{O.D. Maximum - O.D. Minimum}}{\text{O.D. Nominal}} \times 100$$

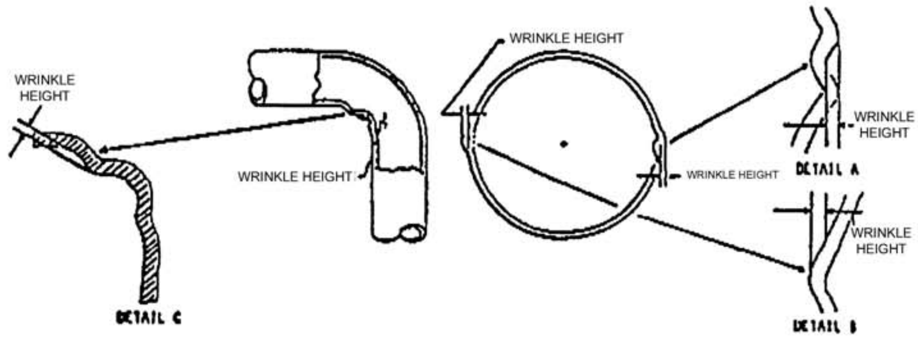


FIGURE 1 - Wrinkle Measurement

3.2 Inspection Criteria for Tube Bends, Hydraulic Tubing:

3.2.1 Classification of Defects: Usability of hydraulic tube assemblies may be effected when values in Table 1 are exceeded. The effect of such deficiencies is classified as follows:

a. Major: Where the defect is likely to cause a malfunction, materially reduce the usability of the parts and render the part unusable for its intended function.

b. Minor A: Where the defect has a slight effect on the usability of the part for its intended purpose. (Detection of these defects may also alert Quality Control to prevailing process deficiencies such as poor workmanship and worn, dirty, or misadjusted tooling which should be corrected to preclude further degradation of the end product.)

c. Minor B: Where the defect has no effect on the usability and covers product appearance or workmanship.

Inspect to ensure that the process is controlled to the acceptability level in accordance with ANSI/ASQCZ 1.4 and Table 2.

TABLE 2 - Inspection Criteria for Hydraulic Tube Bends and Bent Tube Assemblies

Class	AQL	Characteristic	Requirement
Major	1.5	Tube Ovality	Table 1
Minor A	4.0	Tube Wrinkles	Table 1
Minor B	6.5	All Other	3.2.1

4. PRINCIPLES OF TUBE BENDING:

There are several methods of bending tube, pipe, or extruded shapes. However, the economic productivity of a bending facility depends not only on the selection of the most effective method but also on the use of proper tooling and proven techniques. The operator is a factor, but the right equipment and tooling minimize the degree of craftsmanship and expertise required.

Two principles apply to all three primary methods - compression (Figure 2), press (Figure 3), and rotary draw bending (Figure 4). First, the material on the inside of the bend must compress. Second, the material on the outside of the neutral axis must stretch (Figure 5). A fourth method, crush bending, uses press bending to achieve bends. The rotary draw system is the predominate aircraft bending method and is the focus of this AIR.

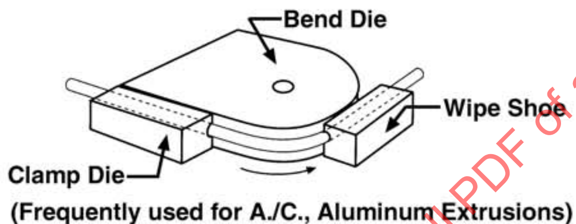


FIGURE 2 - Compression Bending

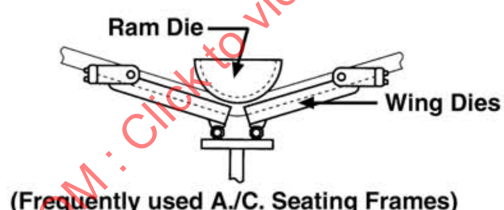


FIGURE 3 - Press Bending

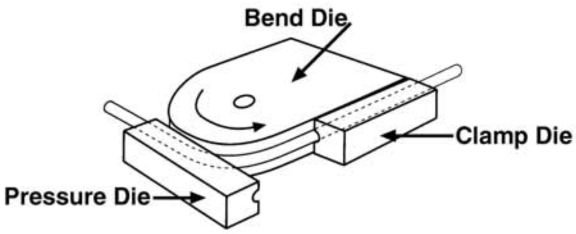


FIGURE 4 - Rotary Draw Bending

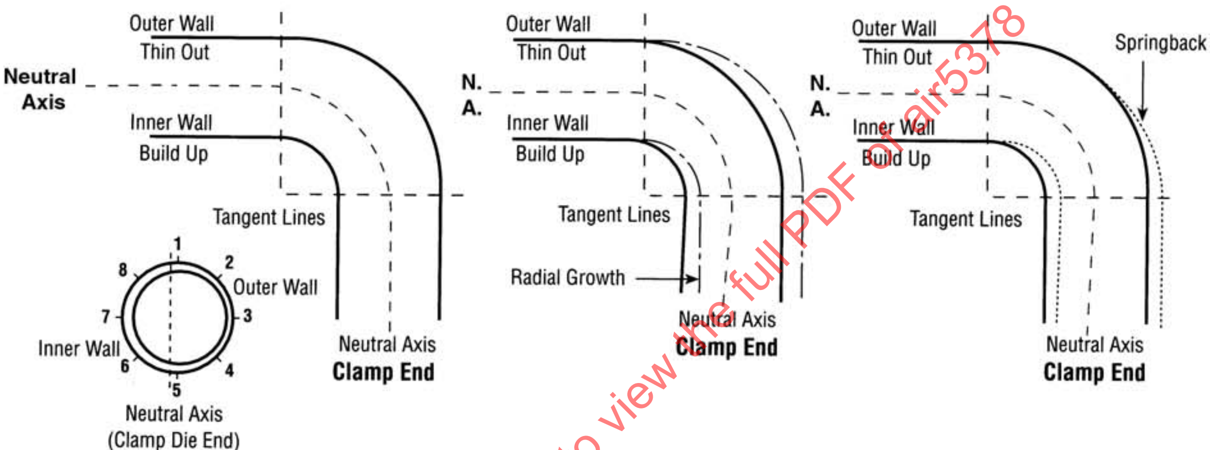
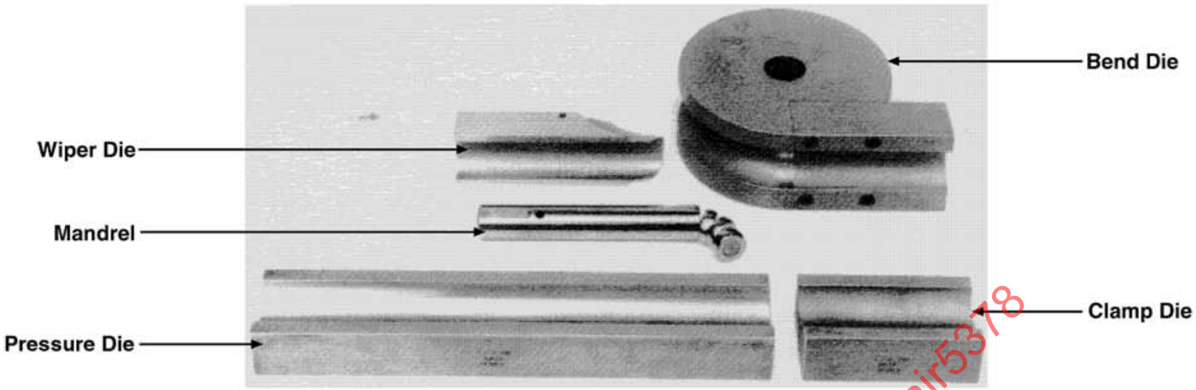


FIGURE 5 - These Drawings Illustrate the Reaction of the Tube to Bending

4. (Continued):

Little or no support is needed within the tube when the tube diameter is small and the wall is relatively thick. Tubes become weaker when the tube diameter increases or wall thickness decreases. In addition, when the bend radius decreases, the forces acting on the tube are effectively increased.

5. ROTARY DRAW BENDING (Figure 6):



Bend die, removable grit blasted clamping insert, clamp die, grit blasted surface, pressure die mirrored surface 180° of travel with 3 x OD mandrel chrome 3 balls "H" regular pitch wiper die square back 4130 with lube holes top and bottom.

FIGURE 6 - 5-Piece Set Rotary Bending Tools

This is probably the most versatile and precise bending method. It consistently produces high-quality bends, even with tight radii and thin tube walls. Only three tools are required for bending heavy-walled tube to a generous radius:

1. The work piece is locked to the bend die (also referred to as radius block) by the clamp die.

2. As the bend rotates, the follower type pressure die advances with the tube.

3. As the wall of the tube becomes thinner and/or the radius of bend is reduced, a mandrel and/or wiper are required (Reference Tooling Selection Guide) (see Figure 6 and 7).

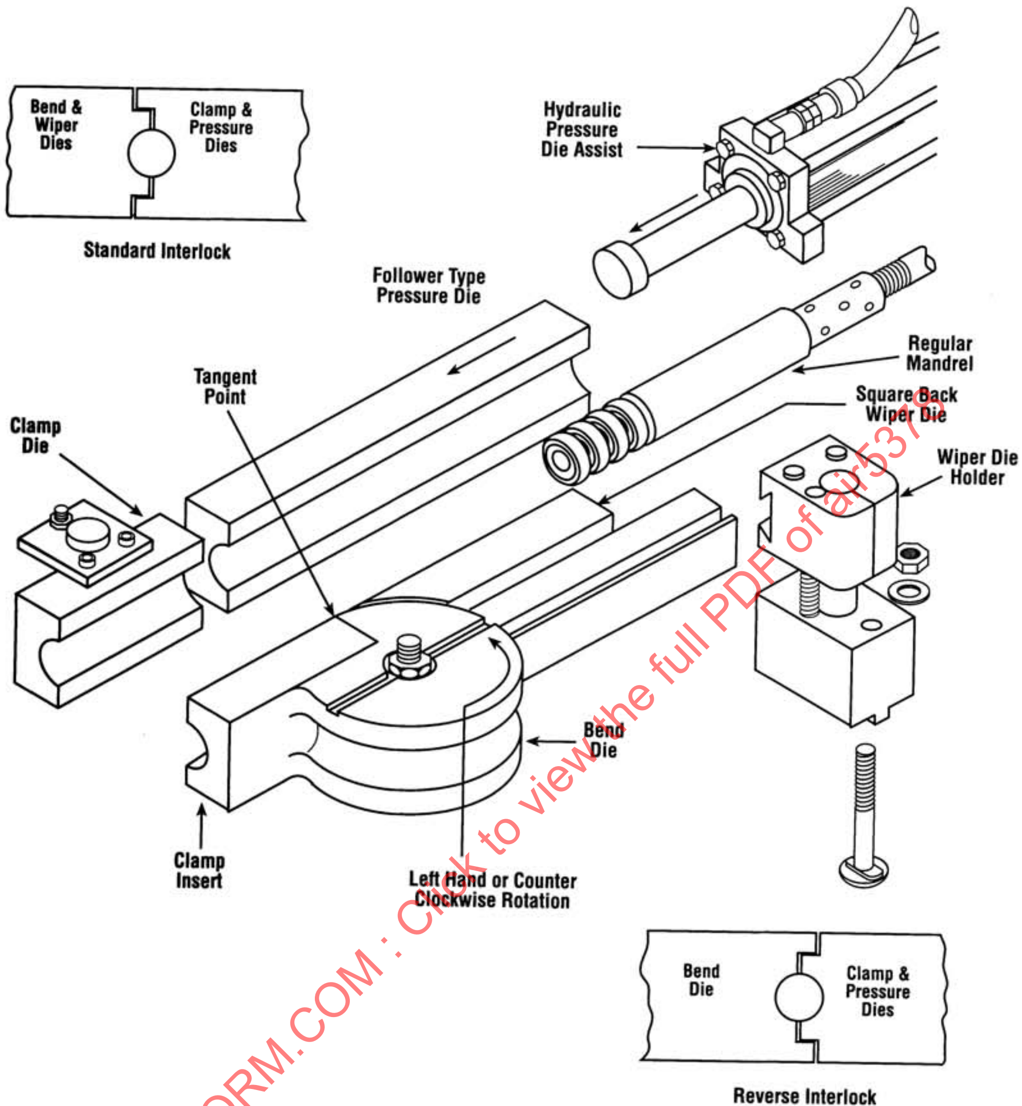


FIGURE 7 - Rotary Draw Bending Tools With Mandrel and Wiper Die

6. SPRINGBACK CONTROL:

“Springback” describes the tendency of metal which has been formed to return to its original shape. There is excessive springback when a mandrel is not used, and this should be a consideration when selecting a bend die. Springback causes the tube to unbend from 2 to 10% of the desired degree of bend, depending on the radius of bend, and this can increase the radius of the tube after bending. The smaller the radius of bend, the smaller the springback. Springback can be affected by the location and pressure of the pressure die (Figure 8). This method can allow a range of radii from one bend die. Material property variations may also have significant affects on the amount of springback.

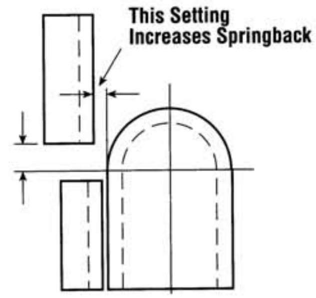


FIGURE 8 - Springback Control

6. (Continued):

The design and manufacture of tools is influenced by several factors. Wall factor and "D" of bend (Reference Figure 25) are the two most critical considerations followed by desired production rate, tubing shape and material, and required quality of bends. The following example illustrates the reasons for various tool designs and bending techniques.

6.1 Example:

6.1.1 Application:

- 1.0 in OD x 0.065 in wall
- 1010 welded carbon tubing to be bent 90° on a 4.125 in centerline radius of bend
- 5 in legs each end
- 120 total parts required - air vent tube
- Wall factor 15 on 4 x D

NOTE: Wall factor = tube OD ÷ wall thickness

6.1.2 Recommendation:

- Bend Die - Type 2, one-piece construction, 3.50 in of clamping (3.50 in x OD), 1020 material (not case hardened because of low production and unusual radius) (see Figure 9).

- Clamp Die - 3.50 in long, heat-treated and nitrided alloy steel material, 50-56 HRC.

- Pressure Die - 3.50 in long, static-type, heat-treated and nitrided alloy steel, 50-56 HRC.

- Tooling Set-up - Bend die is bolted in place. Sample tube is held in clamping area of bend die while clamp die is adjusted to proper pressure. Pressure die is located using minimum pressure. The tube should be painted with a tacky lube in the static pressure die area.

6.1.2 (Continued):

- 1st Bend - No wrinkles, scratches or slip occurred. Clamping marks appeared, and centerline radius of bend is 4.50 in, not 4.125 in.
- Correction - Pressure decreased on clamp die and increased on pressure die to minimize springback.

4.00 in and 5.00 in OD tooling with removable wiper die inserts, serrated grip section, reverse interlock and for pressure die assist of bender.

FIGURE 9 - Tooling, Bend Dies with One-Piece Construction

6.2 Internal, multiple ball, mandrels and wiper dies (Figure 9) help maintain tube bend ovality. They are also essential for tube bends to meet impulse fatigue requirements for hydraulic applications.

7. TYPES OF MANDRELS (Figure 10):

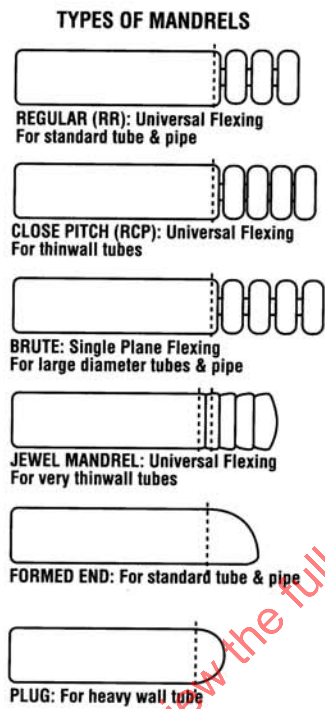


FIGURE 10 - Types of Mandrels

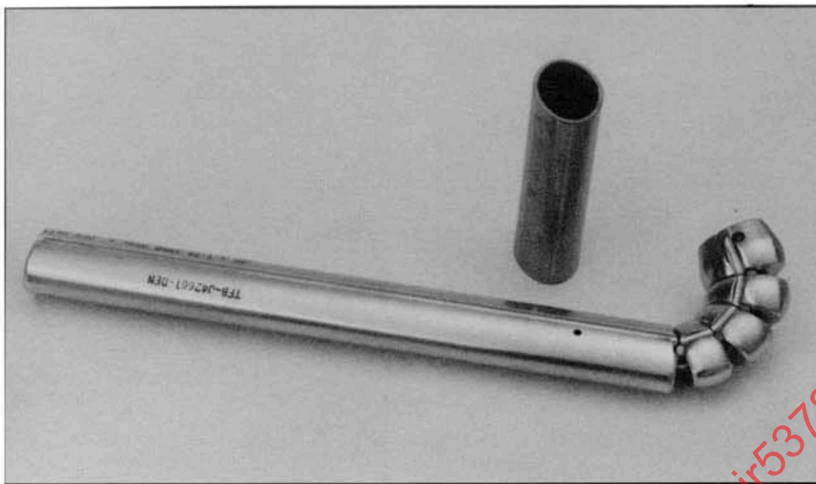
Cable mandrels with flexing nested-saucer segments were used into the late 50's. Since then, the mandrel of choice has been the universal flexing steel-link mandrel in various forms including regular, close-pitch, ultra-close pitch. Single-plane, flexing, and brute mandrels are still being used.

Universal flexing mandrels rotate much like your wrist. Single plane-of-flex mandrels bend like your finger. It is obvious that the ball assembly is located and locked in-line with the bend die tube groove.

The "Brute" mandrel is a single plane-of-flex. It is used when: ultimate mandrel strength is required, for square and rectangular tubing, and for large diameter tubing 3 in and up.

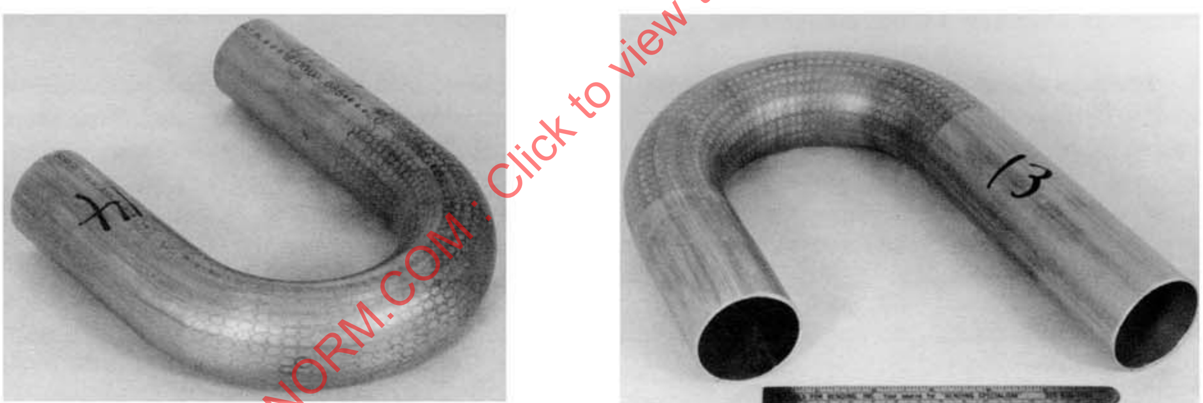
As the wall factor increases and D-of-Bend decreases (Reference Figure 25 on page 25), closer ball support to the tube is improved by reducing the size and pitch of the link. For example, a regular size/pitch link will work with a 1.50 in OD on a 1.50 in Center Line Radius (CLR) bend x 0.065 in wall. When the wall is reduced to 0.042 in, go to a close-pitch mandrel with links down one size from the regular size. With a 0.032 in wall, there is another drop in link size and pitch to an ultra-close pitch mandrel.

Single-plane flexing ball assemblies for mandrels 3.00 in and larger are still in demand. Brute or single-plane flexing mandrel assemblies consistently stay in line with the shank for much easier tube loading. Because the balls are free rotating, wear is evenly distributed (Figure 10A).



4 ball chrome for true oval tubing. "E" plane (Easy) - brute construction grooved 2 places for flash and with lube holes.

FIGURE 10 - Four Ball Mandrel



To visually determine the Neutral Axis, 0.250 diameter circles were etched on an aluminum tube (1.50 OD). It was bent on a 2 x D = CLR (3.0 in) without a pressure die assist or collect boost. NA was at 11:00 looking at clamp die end. With a pressure die assist, NA was at 2:00 and 12% less thinning. Please note elongated circles on the outside of bend and compressed circles on inside of bend.

FIGURE 11 - Neutral Axis

7. (Continued):

The location of the mandrel relative to the point of bend or starting tangent affects the degree of springback. As one example, the mandrel in a forward position (towards clamp) stretches the material on the outside of the bend more than necessary. This increases the length of material on the outside beyond what is required to make a bend. When the bent tube is removed from the bend die, it will conform to the bend die, and there will be less radial growth. Figures 12A is an exaggerated example. The outside of the bend is actually in compression with forces acting at points A and B (Figure 12A). Counteracting forces occur at C and D. Forces A and B tend to close the bend while the forces C and D act to open the bend.

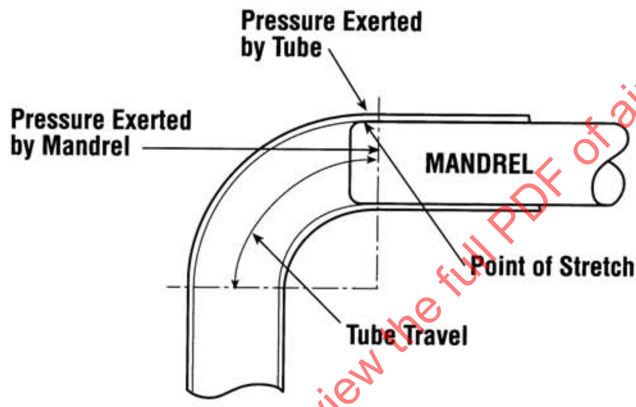


FIGURE 12 - Mandrel Location

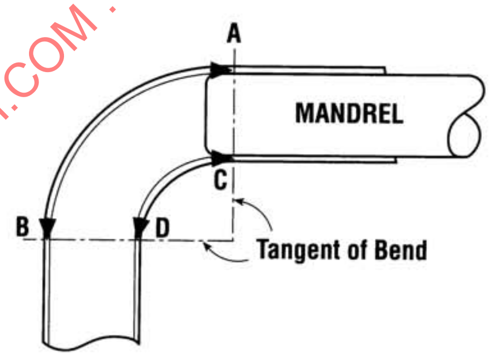


FIGURE 12A - Mandrel Location and Bending Forces

7. (Continued):

The mandrel in a retarded position (away from starting tangent) will not adequately stretch the material on the outside of the bend. Consequently, there is too little material to reach from A to B which puts tension on the material. Now, the forces at A and B are reversed from those shown in Figure 12A and tend to open up the bend. This demonstrates how mandrel location can cause excessive springback reducing the bend angle and possibly increasing the radius. The mandrel must be brought forward (toward clamp) when the radius is increased. However, there is no simple formula for the exact mandrel setting so it should be determined with test bends.

When the tube breaks repeatedly, the material might be too hard for the application. Hard material lacks elongation properties and does not stretch sufficiently. Working with recently fully-annealed material can help preclude this possibility. Breakage can also occur when the mandrel is set too far forward or the tube slips minutely in the clamp die. Slippage problems are discussed later.

7.1 Problem: When Mandrel Too Far Back From Tangent (Figure 13):

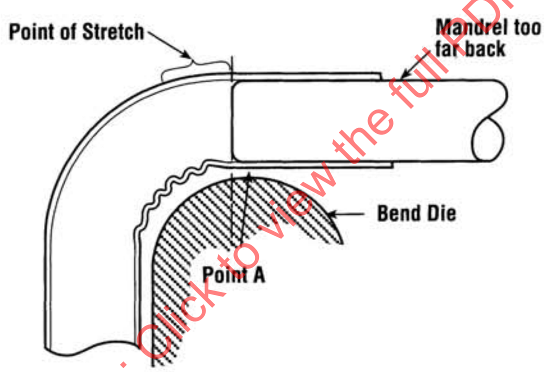


FIGURE 13 - Mandrel Too Far Back

When the mandrel is advanced forward in small increments (towards clamp die), wrinkles may begin to form in back of tangent. At this point, the mandrel is not far enough forward to generate enough pressure on the inside of the bend to compress the material. Initially, the bend may be smooth, but as it progresses past approximately 20°, the material pushes back forming a wrinkle or wave at point A (Figure 13). Continually formed and flattened between the mandrel and the bend die, the wrinkle never entirely disappears. When the bent tube is removed from the bend die and there is a large buckle or kink at point A, it is necessary to continue to advance the mandrel until the material can't squeeze back between the bend die and mandrel.

7.2 Problem: When Mandrel Too Far Forward:

Several problems occur when the mandrel is positioned too far forward. Bumps appear on the outside of the bend and are most evident at the end of bend. A step may begin to appear on the inside at the start of bend. Even though these malformations are shown on the same tube (Figure 14), they will not always appear at the same time depending on tube material, shape of the mandrel, and bend radius. The bump is obviously caused by the mandrel shank, and the step is formed by the end of the mandrel prying the tube away from the bend die.

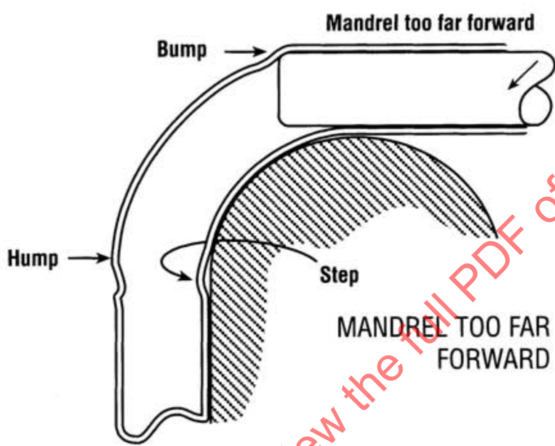


FIGURE 14 - Mandrel Too Far Forward

7.3 Problem: With Undersized Mandrel:

Figure 15 illustrates an undersized mandrel.

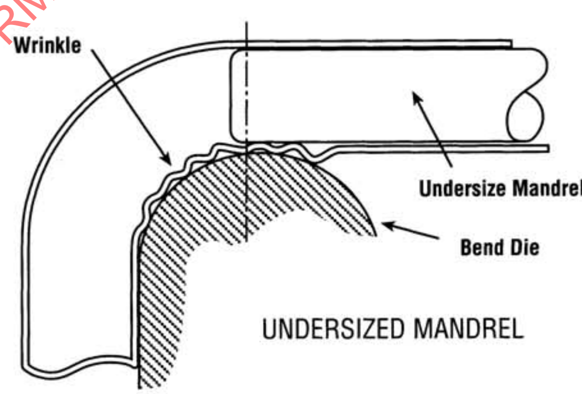
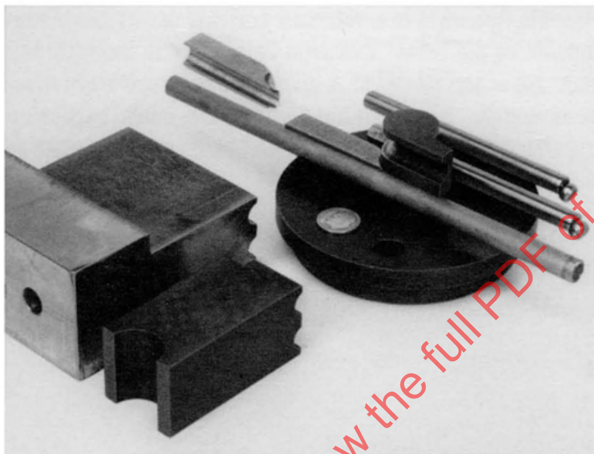


FIGURE 15 - Undersized Mandrel

8. TUBE BENDING USING BALL MANDRELS AND WIPER DIES (See Figure 16):

These two tools are reviewed together because, although they have different functions, they generally perform in conjunction with one another. Ball mandrels and wiper dies are used with the previously discussed tools (bend, clamp, and pressure dies) when the ratio of tube diameter-to-wall thickness exceeds a certain value and bent on a given radius (see Tooling Selection Guide). The wiper die is used to prevent wrinkles. The ball mandrel performs essentially like the plug mandrel with the balls keeping the tube from collapsing after it leaves the mandrel shank.



0.500 x 0.028 on 0.625 CLR bending 2 tubes at a time 180°. Steel wiper dies and chromed ball mandrels. A loading 2-prong fork was used to accurately locate the tubes to tangent, act as a clamping plug.

FIGURE 16 - Two Tube Bending

8.1 Wiper Dies:

The function of a wiper die is to help compress the tubing material without wrinkling or scratches. The tubing hardness will determine the wiper die material. Steel wipers are preferred for aluminum tubing and aluminum/bronze wipers for stainless or titanium. The design and precision manufacturing of a wiper die is extremely critical in order to achieve aircraft quality bends.

Wiper dies are available in the conventional square back configuration (Figure 17). They allow for numerous re-cuttings of both the tube groove and center line radius. A quality wiper die tube groove is ground linearly in the direction of tube travel. While it is cheaper to radially machine this groove, this is not a good bending practice. The tube groove must be parallel to the mounting side and to the center line radius cut. It must also be parallel to the top and bottom sides, particularly when used with interlock tooling.

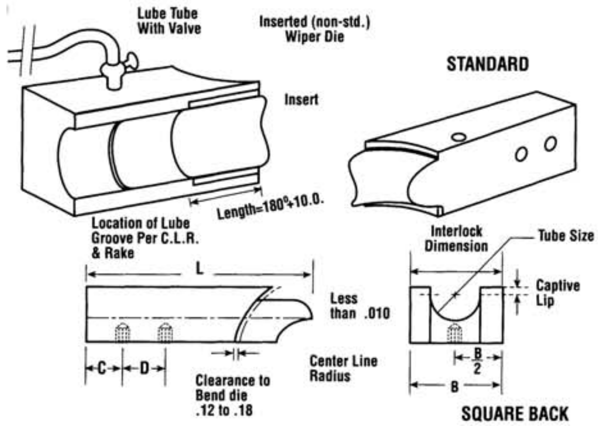
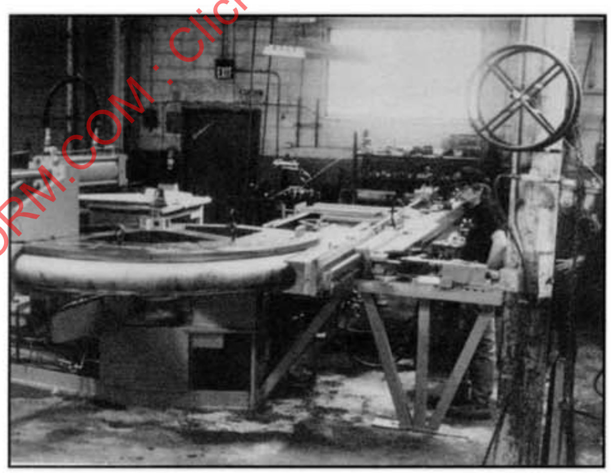


FIGURE 17 - Wiper Dies

8.1 (Continued):

It is important to stress that the tip of the wiper die should be 0.005 to 0.010 in thick depending on the size and material of the wiper die. The tip should never extend past tangent, but it should be set as close as possible. The centerline radius (CLR) machined surfaces should be a given percentage larger than the root diameter of the bend die. This accommodates for rake and some adjustment for wear (Figures 18, 18A, 19, and 20)



Limited production bending to confirm “floor-to-floor” time and consistency of CLR, ovality and minimal tool wear and marking. Note absence of swing arm by using integrally mounted over-head clamping.

FIGURE 18 - Aircraft Ducting - 7.00 in O.D. Tube x 48.0 in CLR

Finish machined but not hardened bend die. Test bending was done to confirm that our calculated compensation for spring-back was correct. Resulting 48 in CLR of bend 90° ± 0.100 in.

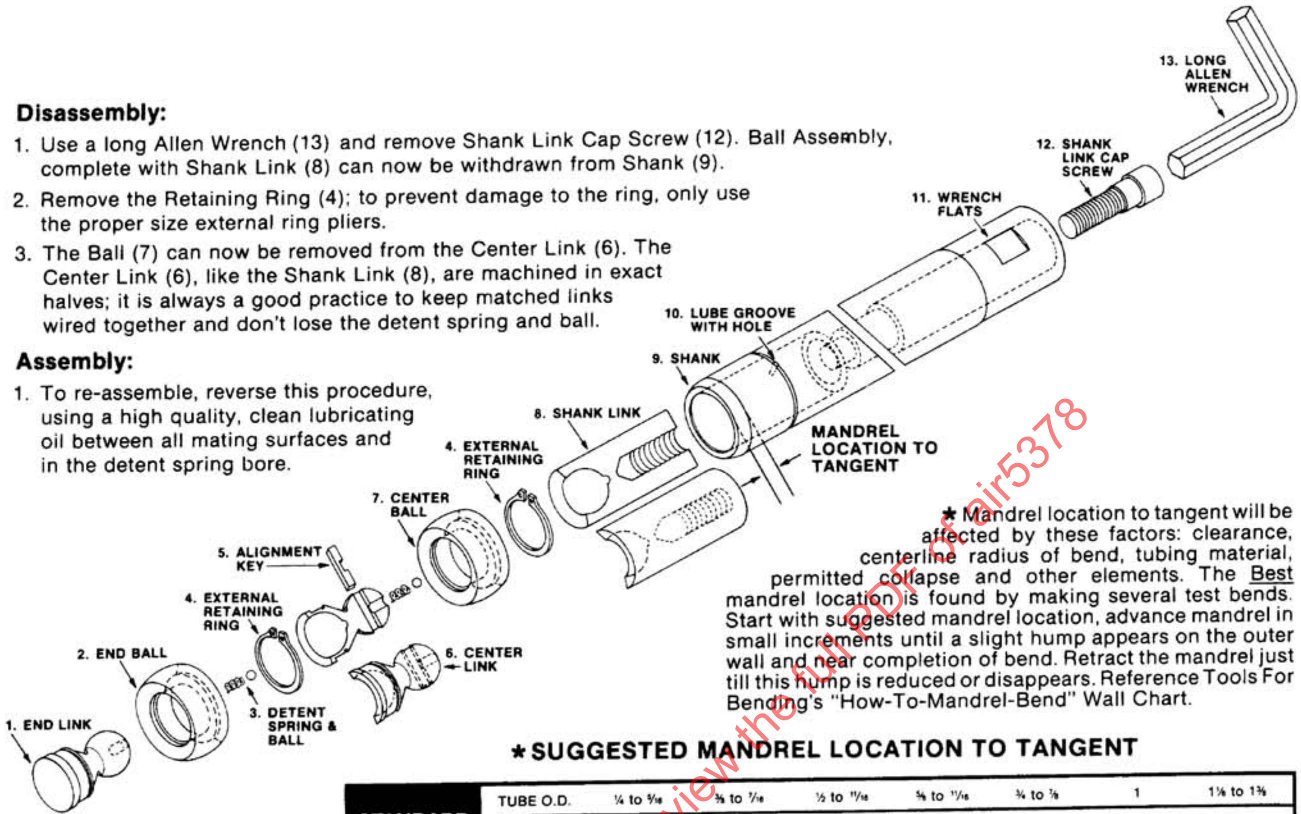
FIGURE 18A - Bend Die

Disassembly:

1. Use a long Allen Wrench (13) and remove Shank Link Cap Screw (12). Ball Assembly, complete with Shank Link (8) can now be withdrawn from Shank (9).
2. Remove the Retaining Ring (4); to prevent damage to the ring, only use the proper size external ring pliers.
3. The Ball (7) can now be removed from the Center Link (6). The Center Link (6), like the Shank Link (8), are machined in exact halves; it is always a good practice to keep matched links wired together and don't lose the detent spring and ball.

Assembly:

1. To re-assemble, reverse this procedure, using a high quality, clean lubricating oil between all mating surfaces and in the detent spring bore.



★ Mandrel location to tangent will be affected by these factors: clearance, centerline radius of bend, tubing material, permitted collapse and other elements. The Best mandrel location is found by making several test bends. Start with suggested mandrel location, advance mandrel in small increments until a slight hump appears on the outer wall and near completion of bend. Retract the mandrel just till this hump is reduced or disappears. Reference Tools For Bending's "How-To-Mandrel-Bend" Wall Chart.

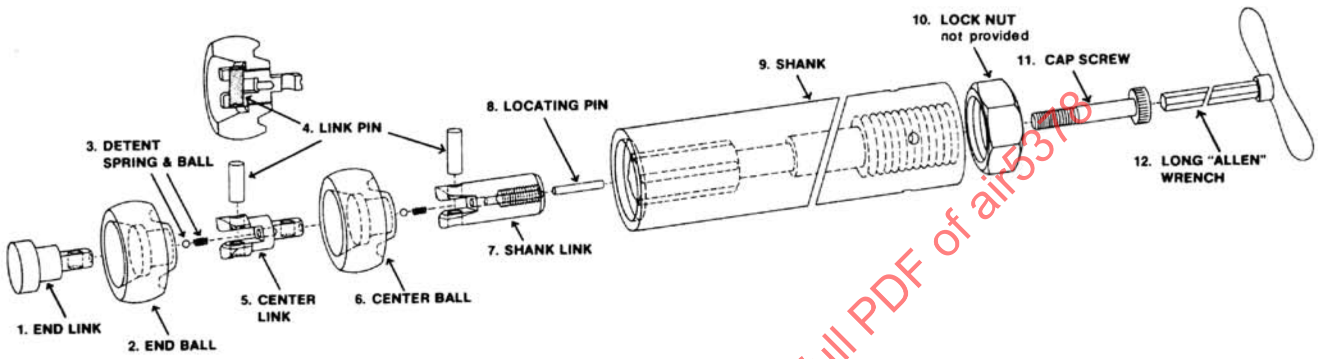
★ SUGGESTED MANDREL LOCATION TO TANGENT

STANDARD PITCH MANDRELS	TUBE O.D.	1/4 to 5/16	3/8 to 7/16	1/2 to 11/16	5/8 to 11/16	3/4 to 7/8	1	1 1/8 to 1 3/8	
	TANGENT	1/16	1/8	1/8	5/32	5/32	3/16	3/16	
	TUBE O.D.	1 1/2 to 1 5/8	1 3/4 to 2	2 1/8 to 2 1/2	2 5/8 to 3 1/4	3 3/8 to 4 1/2	4 5/8 to 5 1/4	5 3/8 to 6	
	TANGENT	7/32	7/32	1/4	5/16	11/32	3/8	7/16	
CLOSE PITCH	TUBE O.D.	1 1/4	1 1/2 to 1 5/8	1 3/4 to 2	2 1/8 to 2 1/2	2 5/8 to 3 1/4	3 3/8 to 4 1/2	4 5/8 to 5 1/4	5 3/8 to 6
	TANGENT	1/16	1/8	5/32	5/32	3/16	3/16	1/4	1/4

FIGURE 19 - Assembly and Disassembly of the More Common Type Regular and Close Pitch Mandrels

ASSEMBLY

First insert the detent springs then balls (3) in their appropriate bores. Assemble each ball and link, starting with the end link (1) and ball (2) by pressing the link pin (4) through each jointed position. After completing the ball and link assembly, the shank link (7) is then inserted into the shank (9). The cap screw (11) is then inserted and tightened. The shank can be rotated (plane of bend) to compensate for wear. When wear does occur on the shank, unscrew the cap screw (11) from shank link (7), slide shank link out of shank link bore. Notice which of the four pin locating grooves the locating pin (8) is situated in, rotate shank link groove to next groove in shank and replace locating pin. Insert shank link into shank and tighten cap screw (11). Caution: to prevent serious damage and/or costly repairs, prior to bending a tube always flex the ball assembly in and around the bend die groove and retighten lock nut (10).



DISASSEMBLY OF BRUTE MANDREL

The ball and link assembly is separated from the shank by removing the cap screw from the mandrel rod end of the shank. Separation of each link from the ball is completed by removing the link pins from each jointed position, care should be taken not to lose the detent springs and balls.

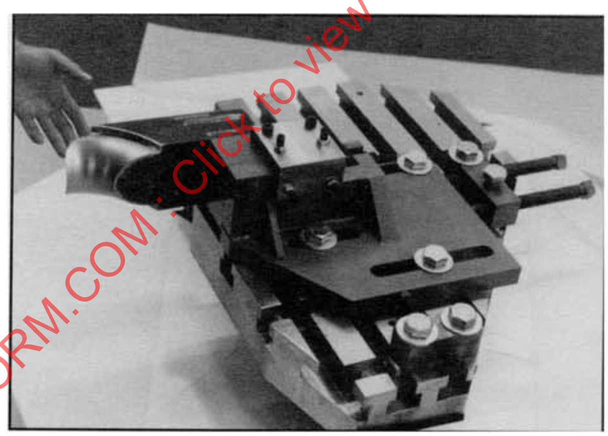
FIGURE 20 - Assembly of Brute Mandrel

8.1 (Continued):

In the early 1960s, wiper die tips or inserts made of aluminum bronze (Figures 21 and 22) were used for bending large diameters of 4.00 in and larger to gain material cost savings. The reduced time it takes to replace a tip is still a benefit. Conceptually, wiper die tips are tempting, but in reality there are problems. Many will not even fit the holder; frequently they are work-hardened and chip; and inferior materials wear out prematurely. When disposable wiper die tips or inserts are used for aircraft type bending, they must be thoroughly inspected and must fit the holder exactly.

Large 5.0 OD and larger aluminum bronze wiper dies for aircraft/aerospace bending. NOTE: Double-ended wipers will be cut in half with substantial savings to customer.

FIGURE 21 - Wiper Die



Steel (not cast iron) wiper die holder designed/manufactured for 6.00 in OD bender. Easily adjusts for rake and location to tangent.

FIGURE 22 - Wiper Die Holder

9. BENDING THIN WALL TUBING:

All of the problems outlined above are greatly magnified when making tight bends or bending thin wall tubing because containing the material during compression becomes increasingly difficult. The pressure is so intense the material is squeezed back past tangent where it is not supported by the bend die and wrinkles (Figure 23). This area must be supported so the material will compress rather than wrinkle, and this is the primary purpose of the wiper die. Note wiper dies cannot flatten wrinkles after they are formed; they can only prevent wrinkles.

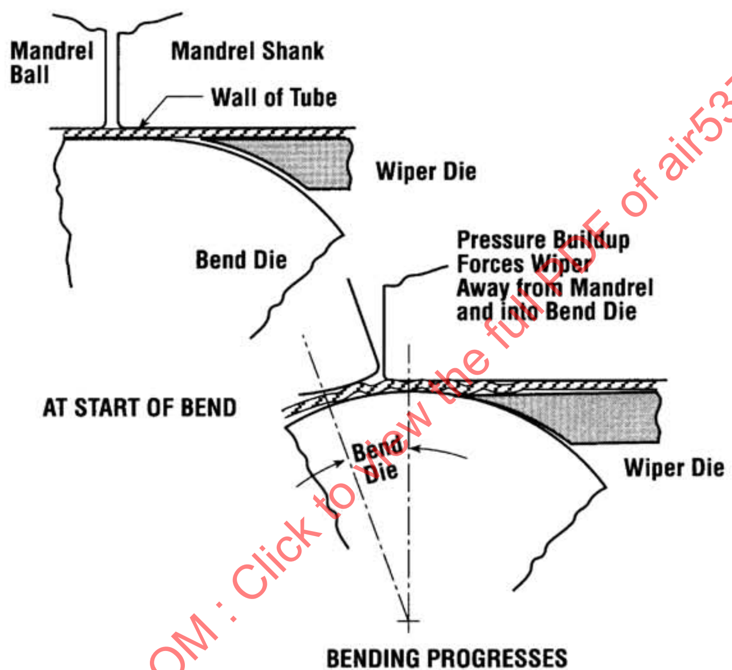
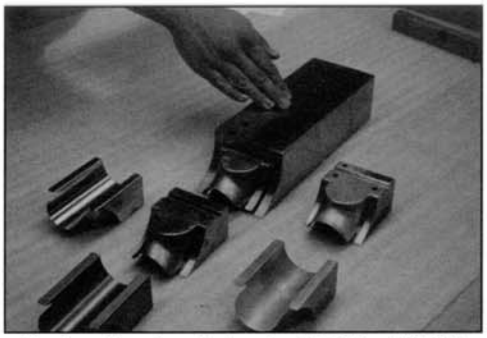
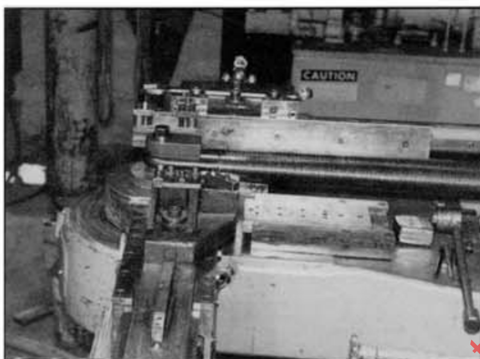


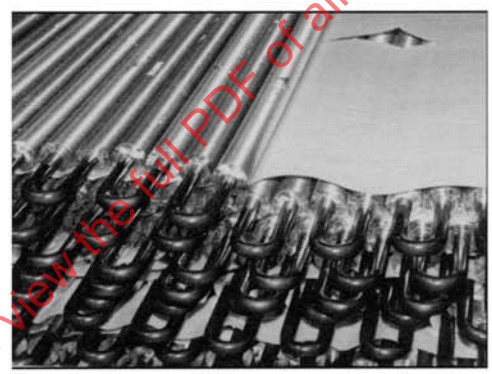
FIGURE 23 - Bend Example

Bending thin wall tubing has become more prevalent in recent years, and tight-radius bends of center line radius equaling the tube outside diameter (1 x D) have accompanied thin wall bending. To compound the problem, new alloys have been developed that are extremely difficult to bend, and the Environmental Protection Agency (EPA) has restricted the use of many good lubricants (Figures 24 and 24A).



Replaceable wiper die inserts, 1.50 OD x 1.50 CLR, furnished here in Ampco Bronze - steel and Kro-Lon® for bending different tubing materials. These inserts provide superior support to the tube, wear much longer and can be quickly and accurately replaced.





Radially-finned tubing bent to 180°. Fins were removed from bending area. NOTE: reverse interlock with Empty-Bending® tube groove on 1.5 x D = CLR.

FIGURE 24 - Tool Examples

5 piece tool set aerospace application. 5.0 OD x 1 x D (5.0 CLR) captive lip, double rotation, close pitch aluminum bronze mandrels (3) and wiper die. 120° with wiper die clearance and horizontal location and lock of clamp die to clamp insert.

Bend die for 10 in OD x 20 in CLR aluminum bronze and steel wiper dies/mandrels for different tubing material. Only 12 in grip length using serrated surface. Die set weighted 3600 lb.

Sink-trap tooling 1.500 x 1.500 copper thin wall. Semi-platform bend die. Chromed wiper tube groove. Chromed mandrel with lube holes.

FIGURE 24A - Tool Examples

9. (Continued):

Tube-bending leaders are successfully meeting these challenges with innovative draw-bending techniques demonstrated by the examples that follow.

- 321 CRES (corrosion resistant) - 2-1/2 in OD x 0.012 in wall on 3 in CL/R 90°
- AM 350 CRES Steel - 1-1/2 in OD x 0.028 in all on 1-1/2 CL/R - 180°
- Titanium A 40 - 4 in OD x 0.035 in all on 6 in CL/R - 90°
- 400 CRES - 1-1/2 in OD x 0.028 in wall on 1-1/2 in CL/R - 180°
- Hastalloy - 3-1/2 in OD x 0.028 in wall on 3-1/2 in CL/R - 45°
- Iconel X - 1-1/2 in OD x 0.018 in wall on 1-1/2 in CL/R - 90°
- Aluminum 6061T6-0 - 2 in OD x 0.028 in wall on 1-3/4 in CL/R - 90°
- 304 CRES - 7 in OD x 0.035 in wall on 7 in CL/R - 180°

NOTE: The most impossible bend imaginable can be achieved! However, the cost to produce it may quickly exclude it from any reasonable consideration (Figure 25).

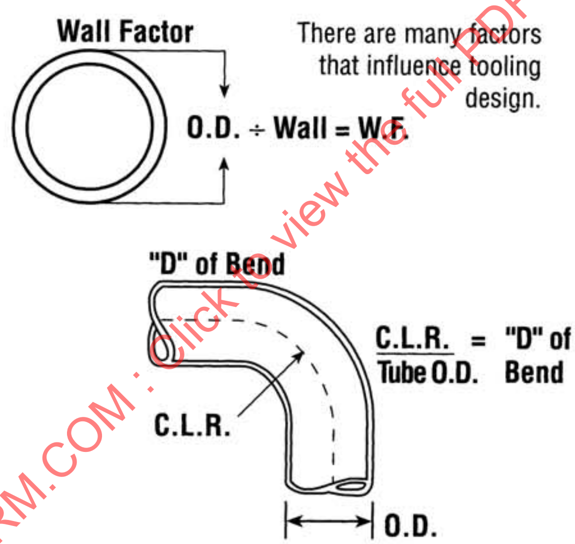


FIGURE 25 - Tool Factors

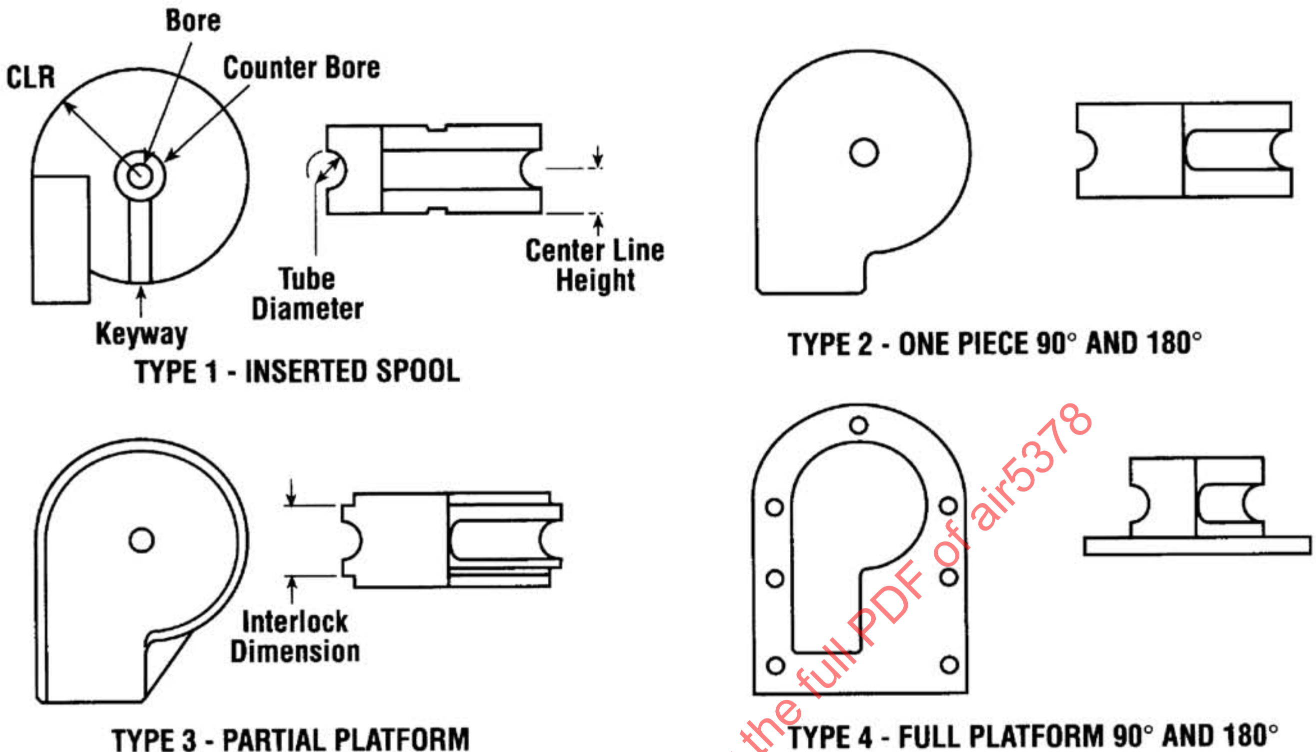
9.1 Example:

9.1.1 Application:

- 2.00 in OD x 0.035 in wall on a 2.00 in centerline radius (CLR) bend.
- Tubing material is 6061-T4 aluminum, one bend 90°, 4 in long legs.
- Tooling to fit "Conrac" No. 72 or equivalent tool with pressure die advance system.
- Total parts 2,000 pieces. Aircraft Quality.
- Wall factor 57 - 1 X D of bend.

Recommendation:

- Bend Die - Type 3 (Figures 26, 26A, and 27), one piece construction with a partial platform for rigidity. Reverse interlocking for ease of set-up and quality bend. Hardened 58-60 HRC, 6 in long clamp. Radius portion to have 0.060 lip or 1.060 deep tube groove to minimize possible tool marks.
- Clamp die - Light grit blast in tube groove for improved grip. Interlocked to bend die for ease of set-up and minimize clamp marks.
- Pressure die - Interlocked to bend die for ease of set-up. Negative lip - preventing pressure die from hitting the bend die. Tube groove with light grit blast to enhance benefit of pressure die advance.
- Wiper die - 4130 alloy material pre-heat treated 28-32 HRC. Interlocked to pressure die.
- Mandrel - close pitch series to prevent wrinkles. Four balls for additional support. Hardened tool steel with hard chrome surface to minimize drag. (Kro-Lon or equivalent surface is not used for soft or non-ferrous tubing.)
- Tooling Set-Up (see Figure 28) - More attention is required to properly position the wiper die and mandrel. The bender is fitted with a pressure die advance to increase pressure applied through the tube against the wiper and bend die without the normal drag which can stretch the wall to rupture. To conserve material and expedite production the work piece will be bent 90° on each end, clamping twice in the center, when parted making two parts.
- 1st Bend - Excessive collapse of over 5% of OD occurred. Wrinkles of 0.040 high appeared only in wiper die area.
- Correction - Mandrel advanced 0.070. The blunt end of the wiper die located closer to the tube reducing rake. Obviously, to achieve a successful bend for this application, several more adjustments would have been made. It is prudent to make only one adjustment at a time.



The proper style of bend dies to be used will be indicated by such factors as tube O.D. x C.L.R., bender sized, degree of bend, etc. Hardened dies are 60-62 HRC with a case depth of .035 - .040. Bending applications requiring precision tools have ground tube grooves, counter bores and all other crucial dimensions.

SPECIFY

1. Tube O.D. and Wall
2. Center Line Radius
3. Make and Size of Bender
4. Degree of Bend
5. Rotation of Bender
6. Interlock Dimension
7. Desired Production

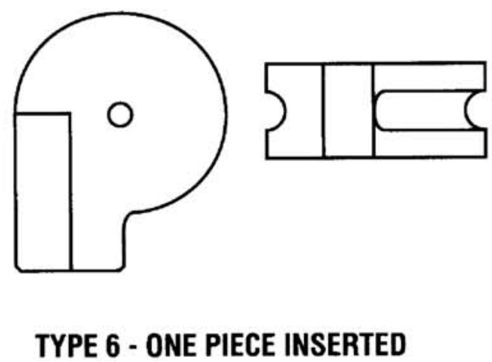


FIGURE 26 - Type 6 - Bend Dies

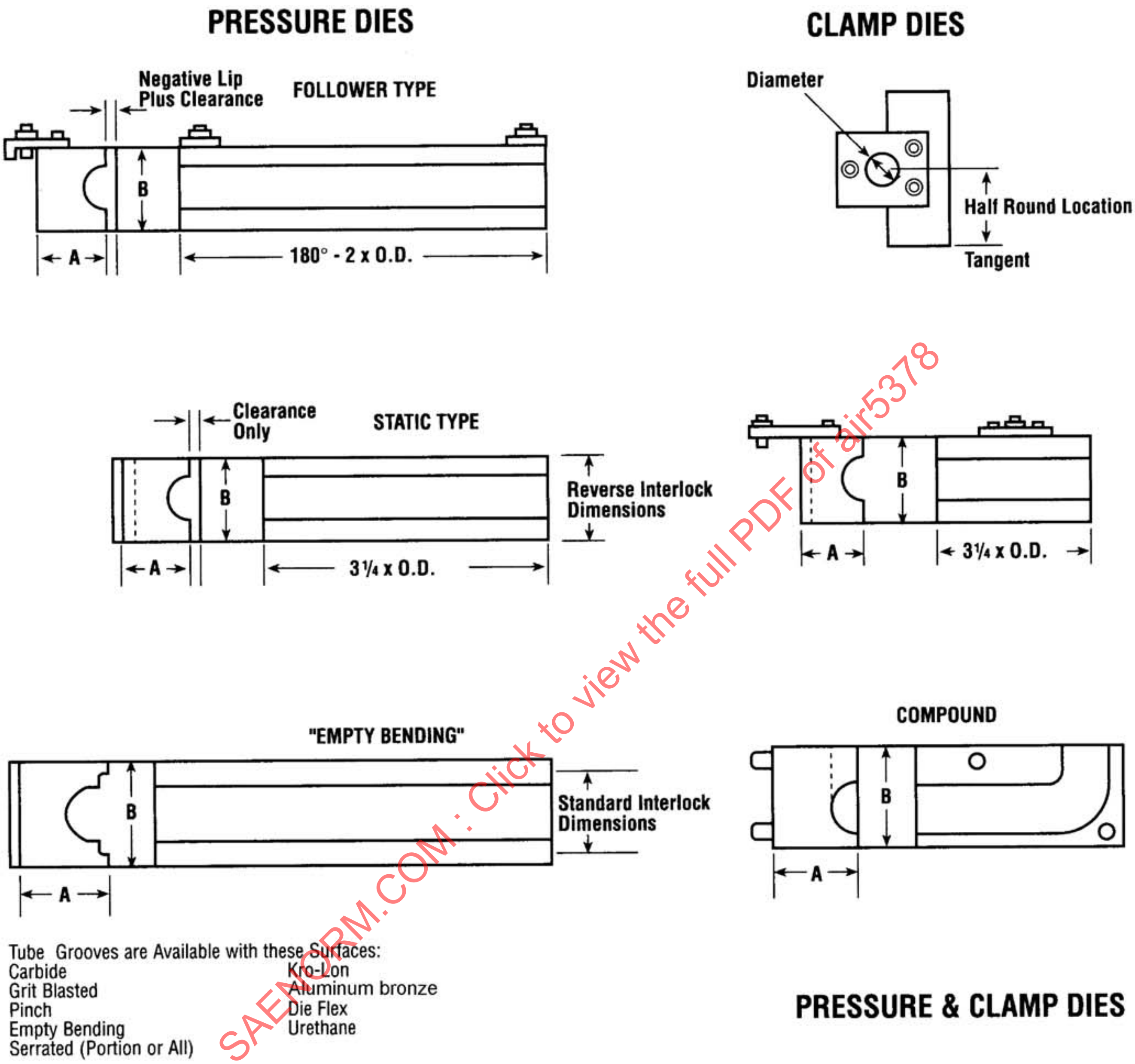
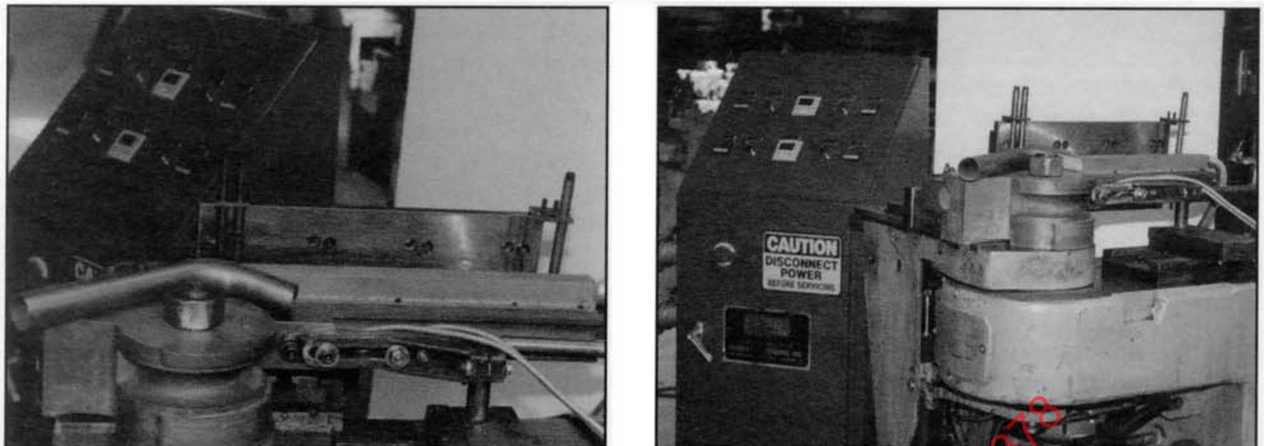
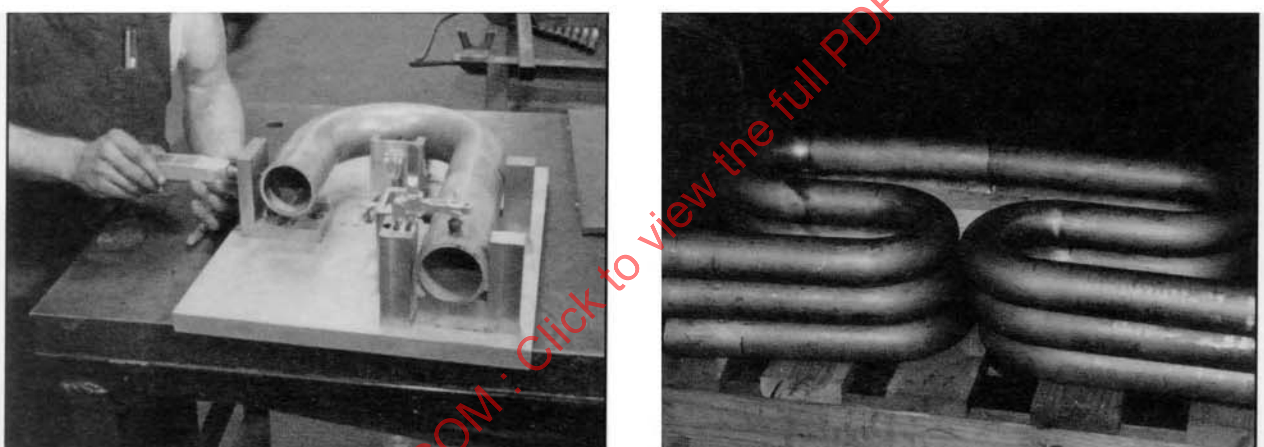


FIGURE 26A - Pressure and Clamp Dies



Heated tool set for thin wall titanium aerospace application. In-house test bending included pressure die assist. High-temp lube complete with control cabinet and enough electrical input to dim the lights of Denver.



Checking fixture to confirm 180° of bend, parallel legs, and flatness after making 2nd 180° bend.

FIGURE 27 - Tooling Examples

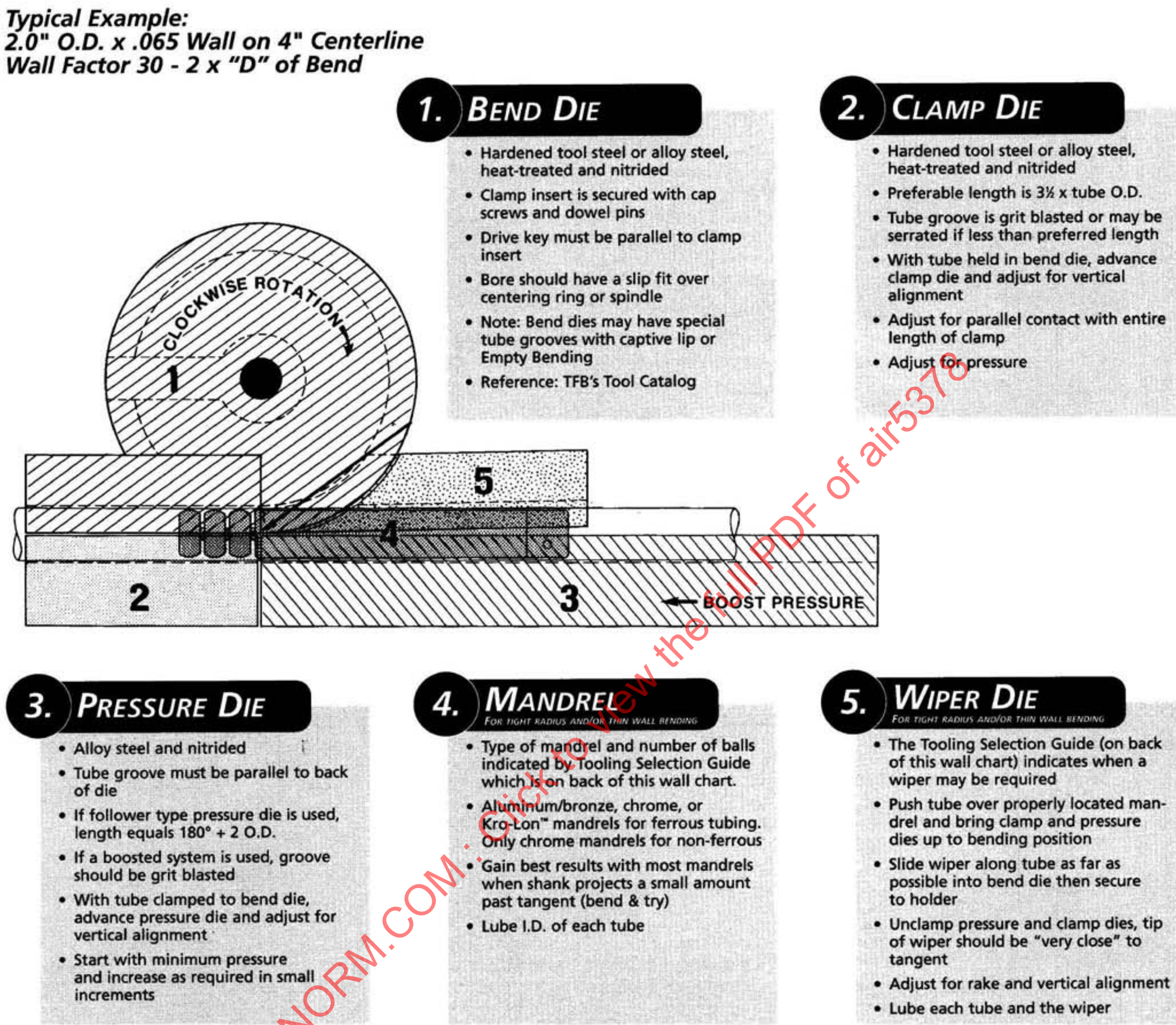


FIGURE 28 - Design and Set-Up of Tooling

10. THIN WALL BENDING APPLICATIONS:

Typically, aerospace and aircraft tube bending is characterized by a number of factors: (1) tight radius bends some less than 1 x D (CLR ÷ tube OD); (2) high wall factors of 100 plus (tube OD ÷ wall); (3) often, too little or no straight between bends; (4) minimal permitted wall thinning (12 to 18%) and collapse (3 to 6%); (5) wide range of tubing material, many with very poor elongation (12 to 18%) and high cost; (6) low production with many frequent tool changes.

For thin wall tube bending, there are special considerations regarding the material to be bent. To ensure consistent tubing dimensions and characteristics, all material required for a job should be procured from one supplier, preferably from the same lot or heat number. Premium-priced close-tolerance tubing should be considered because it will often save many times the added cost. It is often cost effective to size batches of tubing that best fit several mandrels for the same OD and wall before bending. When the inside finish of a tube is a critical factor, the ID of the tube can be electro-polished before bending, and extreme care should be taken to protect the finish during bending.

10.1 Guidelines for Thin Wall Bending:

The tubing should be a firm slip fit on the mandrel and clearance should not exceed 10 to 15% of wall thickness. This same clearance also applies to the four pieces of outside tools. The tube material specifications and characteristics found in tubing catalogs are very helpful. For example, the rated ductility and elongation of a material may indicate the need for special bending methods such as heated tools, positive "Boost" bender, and even mandrel oscillation (Figure 29).

Aircraft/aerospace bending 7.0 OD x 7 in CLR x 0.032 wall. Note full platform, reverse interlocking, removable grip section. Aluminum bronze wiper die and close pitch 8 ball mandrel (not shown).

FIGURE 29 - Tooling

10.1 (Continued):

Few tube machines are capable of bending thin wall, 1 x D tubing. Even machines designed for this special bending must be in excellent condition and be large enough to assure tooling rigidity. Any sources of appreciable loss of rigidity of tooling members should be eliminated. The machine spindle should have less than 0.0005 in total indicated run-out. The mandrel rod should be as large as possible to eliminate its stretching. Wiper dies and their holders must be solid. Clamp and pressure die slides and tool holders must be tight.

A full complement of controls is essential for bending thin wall tubing. The machine must be capable of retracting and advancing the mandrel with the clamp and pressure dies closed. A direct acting hydraulically-actuated pressure die is desirable because it provides consistent pressure on the tube regardless of wall variation (Figure 30).

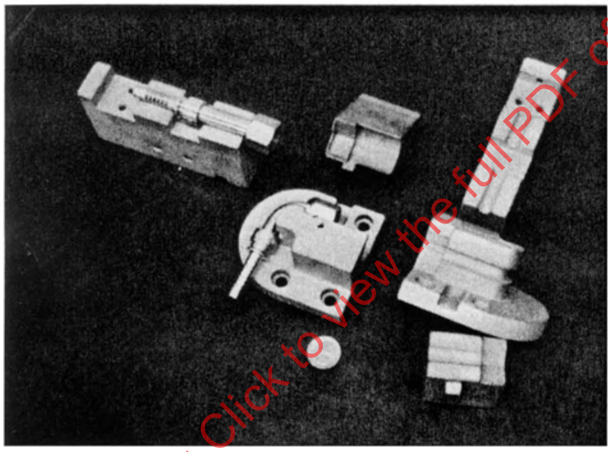
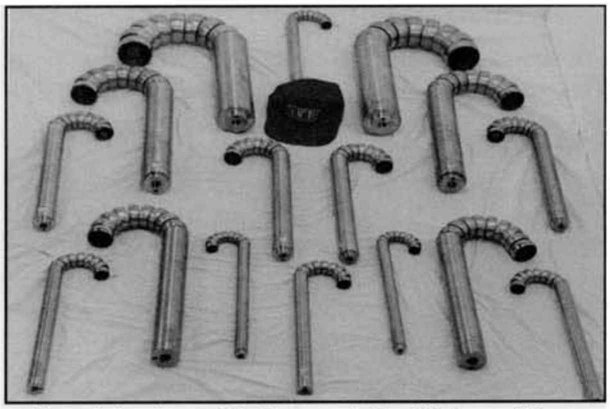


FIGURE 30 - Tool Set for One-Piece Fittings on Conventional Bender

A pressure die advance should also be available. This counteracts the drag of the pressure die, mandrel, and wiper die, and pushes the tube into the bending area which prevents excessive wall thin-out (Figure 28).



Assorted universal flexing mandrels. All close pitch type/1 in OD thru 4.0 in.

FIGURE 31 - Mandrels

10.1 (Continued):

Without a pressure die advance, the normally-expected thinning is about three-quarters of the elongation of the outer wall. Therefore, a 2.00 in tube bent to a 3.00 in center line radius will thin about 25%, and the cross-section of this bend is shown in Figure 32. As the compressive yield stress is generally higher than the tensile value, the neutral axis (that portion of the tube that is not stretched or thinned out) will be inside the geometric axis of the tube. Since distortion is proportional to the distance from the neutral axis, thinning of the outside of the bend may be greater than thickening of the inside.

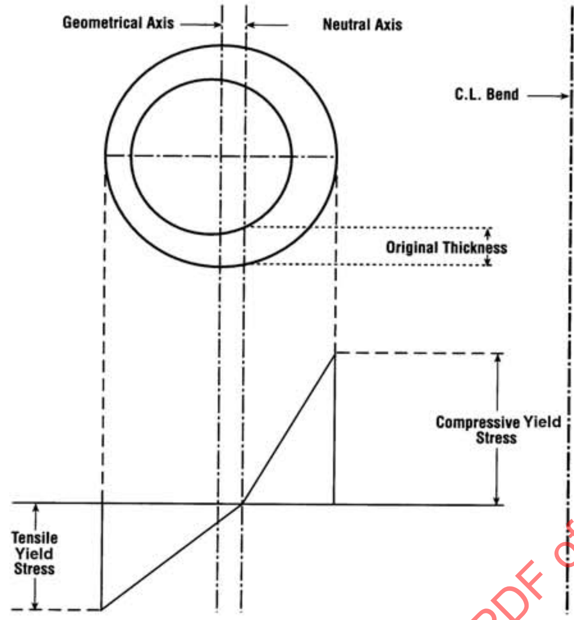


FIGURE 32 - Tubing Cross Sections Without Pressure Die Assist

10.1 (Continued):

Moving the neutral axis towards the outside of the bend will reduce thinning (Reference Figure 11). Theoretically, when the neutral axis coincides with the outer wall, thinning is eliminated but heavy thickening occurs on the inside. There are two methods of moving the neutral axis. First, put the tube into compression before bending commences which modifies the stress distribution in the section as shown in Figure 33. A second method is to reduce the compressive-yield stress of the material. This is accomplished by heating the part of the tube that will form the inside of the bend which yields a stress pattern as shown in Figure 34.

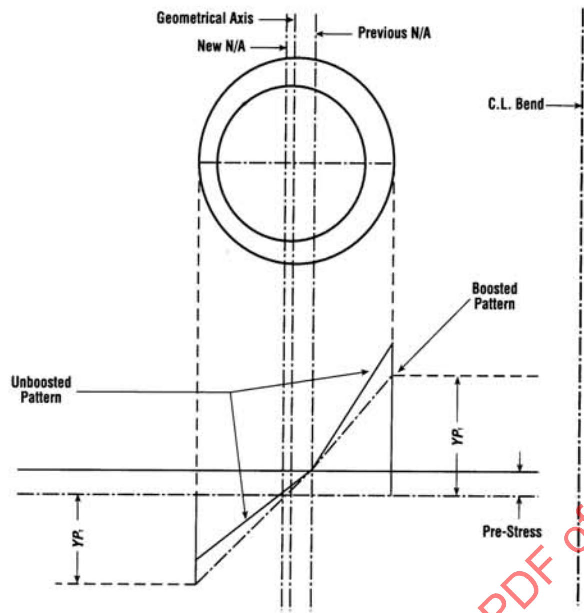


FIGURE 33 - Tubing Cross Sections With Pressure Die Assist

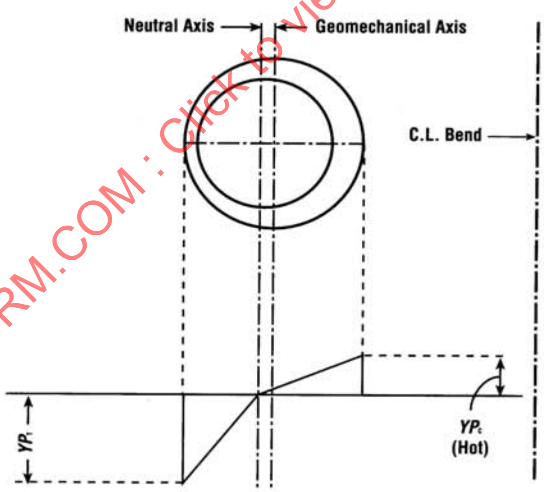


FIGURE 34 - Tubing Cross Sections With Heated Tube and/or Tools

10.1 (Continued):

Thinning can be substantially reduced when both methods are employed simultaneously. It is not necessary to reduce wall thinning much more than 10% so the extra advantage can be gained in terms of closer bend radii or lighter-walled tubing. The pressure-die assist should push the pressure die and tube separately or simultaneously.

A clamping plug (Figure 35) should be used when the wall is so thin it is distorted by the clamp die or collapses under the clamp-die pressure. It also helps eliminate slippage with very short clamp dies and with less clamping pressure. A clamping plug should be a press fit. It is placed in the clamping area prior to closing the clamp die and removed before the pressure die is opened. Expanding clamping plugs are also available to make insertion and removal easier. They are designed to accommodate wall variations, as well as different walls for tubing with the same OD.

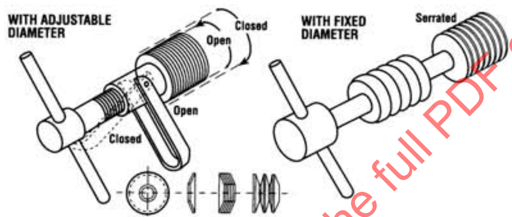


FIGURE 35 - Internal Clamp Plugs

10.2 Lubrication:

Both the quality and quantity of lubricant used are extremely important. One lubricant will not work equally well on all materials. For example, ferrous and non-ferrous materials may require different lubricants. The EPA does not permit the use of some of the best-performing lubricants because of their high chlorine and sulfur content and their effect on the ID of the tubing. Considerable research and development resulted in special biodegradable and acceptable lubricants which are now available.

A controlled amount of lubricant can be applied to the mandrel and inside the tube. The lubricant must cover the entire inside of the tube. Wiper dies, and especially mandrels, can be machined to permit auto-lubrication (Figure 36).