PFI Standard ES-24
(Reaffirmed - September 2010)

PIPE BENDING METHODS, TOLERANCES, PROCESS AND MATERIAL REQUIREMENTS

Prepared by

Pipe Fabrication Institute Engineering Committee

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PIPE FABRICATION INSTITUTE

Dedicated to Technical Advancements and Standardization in the Pipe Fabrication Industry
Since 1913

USA
511 Avenue of America's, # 601
New York, NY 10011

CANADA
655, 32nd Avenue, # 201
Lachine, QC H8T 3G6

WEB SITE
www.pfi-institute.org

Pipe Bending Methods, Tolerances, Process and Material Requirement

METRIC CONVERSIONS

The conversion of quantities between systems of units involves a determination of the number of significant digits to be retained. All conversions depend upon the intended precision of the original quantity and are rounded to the appropriate accuracy.

Pipe sizes together with applicable wall thicknesses are not shown with metric equivalents.

The SI (metric) values where included with the customary U.S. values in this Standard are the rounded equivalents of the U.S. values and are for reference only.

Metric units were derived utilizing the following conversion factor:

Conversion	**Factor**	**Conversion**	**Factor**
Inches to Mitlimeters	25.4	Deg. Fahr. to Deg. Cent.	5/9 (Deg. F.– 32)
Lb/in^2 to Kg/cm^2	0.0703		

1. Scope

1.1 This standard covers methods, process requirements, tolerances and acceptance criteria for shop fabricated pipe bends.

1.2 The bending methods described in this standard are a partial representation of commonly used processes and do not preclude the use of other methods.

2. Terminology

2.1 The symbols and terms defined below are used throughout this standard:

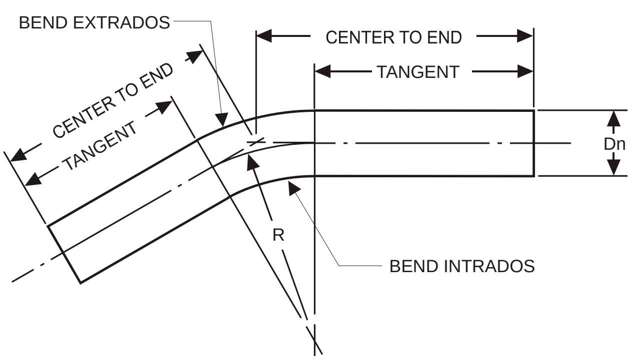


FIGURE 2.1

D = Nominal pipe size.

Dn = Nominal outside diameter of pipe.
tn = Nominal wall thickness of pipes.
tm = Minimum calculated wall thickness required by the applicable code.
T = Pipe wall thickness (measured or minimum, in accordance with purchase specification).
R = Center line radius of bend.

3. Bending Methods

3.1 This standard covers bends formed by both hot and cold bending methods. For this standard, a temperature 100 degrees F below the lower critical temperature of the material is defined as being the boundary between hot and cold bending.

3.2 Unless otherwise specified by the governing code, the bending procedure, including the heating/cooling cycle and post bend heat treatment, is determined by the pipe material, diameter, wall thickness, bend radius and the required properties after bending. Because of the many variables involved, the bending procedure should be determined by the fabricator.

3.3 While the bending equipment used in many of the methods is generically the same, there may be differences in bending procedures, material allowances, hold and pull legs, wall thickness, etc., between bending fabricators.

3.4 **Hot bending methods**

3.4.1 FURNACE BENDING:
In this method, the pipe is firmly packed with sand and then heated in a furnace to a temperature in the range of 2000 degrees F. After removing from the furnace, one end of the pipe is retained in a holding device and a bending moment is applied at the other end. The radius of the bend is controlled by dies, stops or templates as the pipe is bent. For long radius bends and/or heavy wall pipe, the sand filling operation may not be necessary.

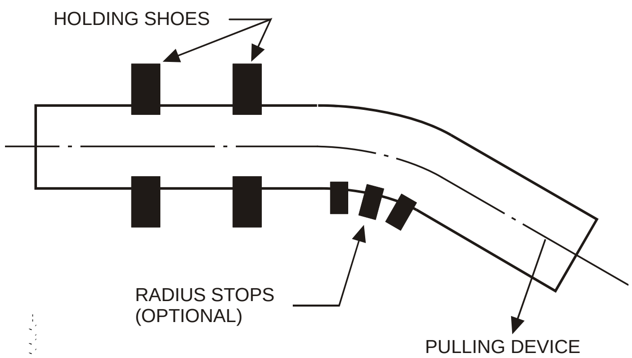


FIGURE 3.4.1
FURNACE BENDING

3.4.2 INCREMENTAL BENDING:
The incremental bending equipment is composed of an anchor box, a hydraulic cylinder, and a moveable heating device. The pipe is clamped in the anchor box and the front tangent is connected to the hydraulic cylinder. The heating device heats a narrow circumferential band on the arc to the proper bending temperature. A force is then applied by the hydraulic cylinder to bend the small increment a predetermined amount. The heating device is then moved to successive segments where the process is repeated until the required arc is attained. After bending each increment, the heated area is cooled as required by the appropriate bending procedure.

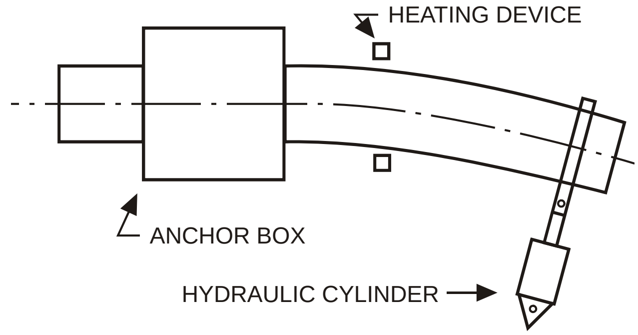


FIGURE 3.4.2
INCREMENTAL BENDING

3.4.3 INDUCTION BENDING:
The induction bending equipment is composed of three basic components consisting of a bed, a radial arm, which is set at the required radius, and an induction heating system. The pipe is placed in the bed and the front tangent is clamped to the radial arm. The induction heating system heats a narrow circumferential band around the pipe to the appropriate bending temperature. When this temperature is reached, the pipe is continuously moved through the heating coil while a bending moment is applied to the heated area. After passing through the coil, the pipe may be either forced or naturally cooled as required by the appropriate qualified bending procedure.

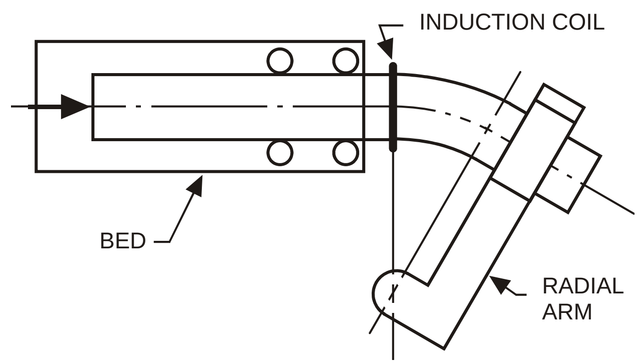


FIGURE 3.4.3
INDUCTION BENDING

3.5 **Cold bending methods**

3.5.1 ROTARY DRAW BENDING:
In this method, the pipe is secured to a bending die by a clamping die. As the bending die rotates, it draws the pipe against the pressure die and, if necessary to prevent wall collapse, over an internal mandrel. The pressure die may remain fixed or move with the pipe.

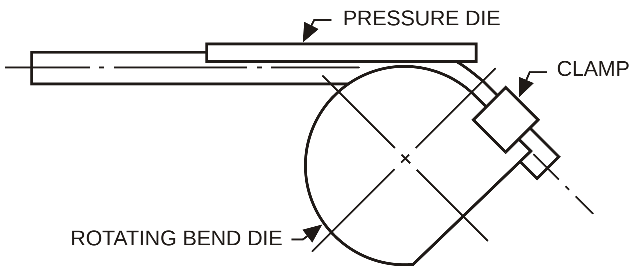


FIGURE 3.5.1
ROTARY DRAW BENDING

3.5.2 RAM BENDING:
In ram bending, the pipe is held by two supporting dies and a force is applied by means of a hydraulic ram to a forming shoe located at the center of the workpiece. The supporting dies rotate on their mounting pins so that they follow the pipe and maintain external support throughout the operation.

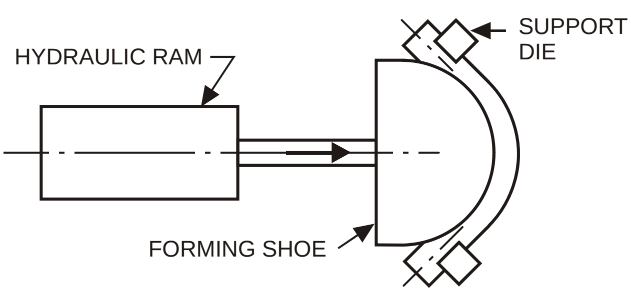


FIGURE 3.5.2
RAM BENDING

3.5.3 ROLL BENDING:
In roll bending, three forming rolls of approximately the same diameter arranged in a pyramid are used. The two fixed rolls oppose the adjustable center roll. The pipe is passed through the rolls with the position of the adjustable roll controlling the bend radius.

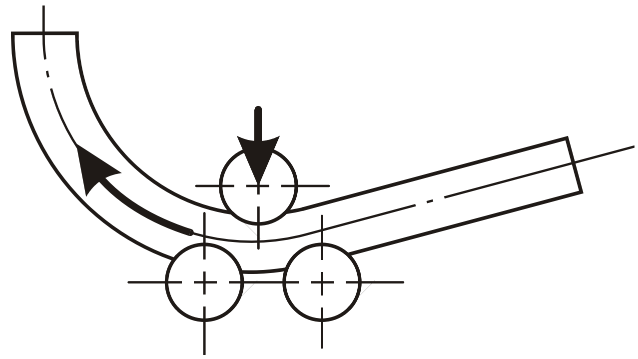


FIGURE 3.5.3
ROLL BENDING

4. Welds in Bends

4.1 In some instances it is not practical to utilize pipe of sufficient length to satisfy the required arc length of the bend. When it becomes necessary to join lengths of pipe resulting in a circumferential butt weld in the arc of a pipe bend, the following practices should be considered:

4.1.1 Pipes to be welded should be selected to provide the best uniformity possible at the mating ends. Pipe wall thickness shall not be less than the design minimum plus bend thinning allowance (see section 7.0).

4.1.2 End preparation for welding shall be in accordance with the qualified welding procedure to be used. Internal counterboring should be avoided wherever possible. During fit-up of the joint, the pipes should be rotated or aligned as necessary to provide the least amount of I.D. and/or O.D. mismatch and the best transition across the weld.

4.1.3 The welding procedure must be qualified in accordance with the governing Code for the thermal exposures, (if any) excepted in bending and heat treatment.

4.1.4 After completion of the circumferential butt weld, but before bending, the O.D. and I.D. (where accessible) of the weld should be ground to remove excess weld reinforcement and blended smoothly into the base metal.

4.1.5 It is good practice to examine the circumferential butt weld by radiography prior to and after bending, whether or not such radiography is required by the applicable Code.

5. Linear and Angular Tolerances

5.1 Bends shall be provided with a total angularity tolerance of ± .5 degrees as determined by the intersection of the tangent centerlines measured by appropriate equipment.

5.2 When the fabricator is required to provide bends cut to a specified center-to-end dimension it shall be to the tolerances specified in PFI ES-3.

5.3 If intermediate portions of the bend profile are essential, their tolerances shall be a matter of agreement between the purchaser and the fabricator.

5.4 See fig. 9.3 for an explanation of terminology regarding bend tolerances.

6. Form Tolerances

6.1 The ovality of a pipe bend shall not exceed the ovality required by the governing code. If there is no governing code, the difference between the maximum and minimum diameters shall not exceed 8% of the average measured outside diameter of the straight portion of the pipe unless by mutual agreement between the purchaser and the fabricator. Where operating conditions require less ovality it may be necessary to use larger radii, heavier pipe walls or a specific bending method that will provide a closer control of ovality.

6.2 Since there are occasions when buckles cannot be avoided, the following restrictions should apply:

(a) All wave shapes shall blend into the pipe surface in a gradual manner.

(b) The maximum vertical height of any wave, measured from the average height of two adjoining crests to the valley, shall not exceed 3% of the nominal pipe size. (See Figure 6.2, Note 1)

(c) The minimum ratio of the distance between crests as compared to the height between crests and the included valley should be 12 to 1. (See Figure 6.2, Note 2)

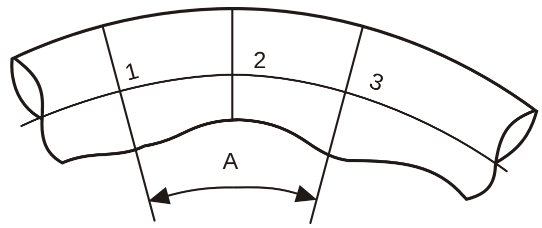


FIGURE 6.2
APPLICATION OF PIPE WALL BUCKLING TOLERANCES

Note 1 – Depth of average crest to valley is the sum of the outside diameters of the two adjoining crests divided by two, minus the outside diameter of the valley.

$$\text{Depth} = \frac{(OD)_1 + (OD)_3}{2} - (OD)_2$$

Note 2 – Ratio of distance between crests to depth is:

$$\frac{A}{\text{Depth (per Note 1)}} \geq \frac{12}{1}$$

6.3 Buckles which exceed the above tolerances will be subjected to corrective action to bring them within tolerance.

6.4 If operating conditions require tighter tolerances on buckles, it may be necessary to use larger radii, heavier pipe walls or a specific bending process.

6.5 To determine what bends can be produced with a satisfactory degree of quality, the Pipe Fabrication Institute has conducted studies on carbon steel and low alloy steel hot bends to determine minimum recommended bend radii for various ratios of outside diameters to wall thickness. The resulting bending range determined by these studies for each of the bending processes is shown in Figure 6.5.1 and 6.5.2.

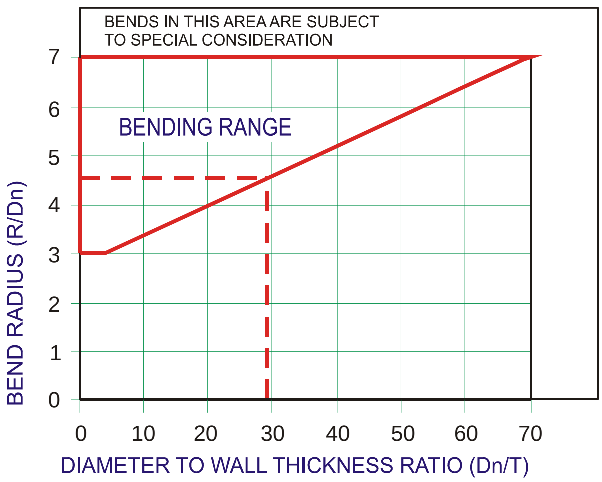


FIGURE 6.5.1
FURNACE BENDING RANGE

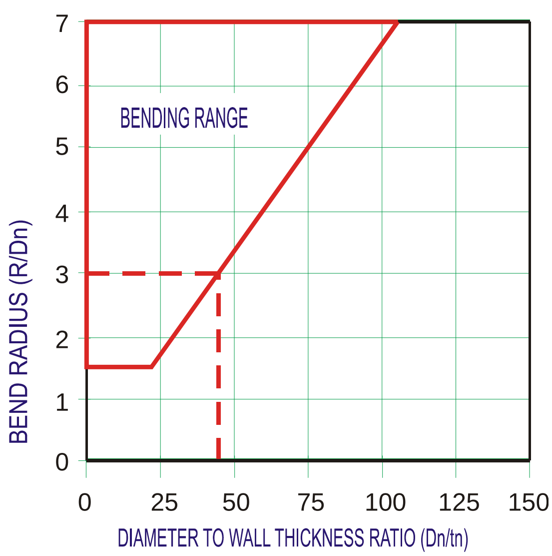


FIGURE 6.5.2
INDUCTION AND INCREMENTAL BENDING RANGE

6.6 Two examples are given for the determination of minimum recommended wall thickness and bending radius combinations for a given pipe size.

Example A: Determine minimum permissible bending radius required for furnace bending 12"-Extra Strong carbon steel pipe per ASTM A 106-Grade B.

(1) Determine the diameter to wall thickness ratio. 12" X-Stg. is 12.75" O.D. with a .500" nominal wall. Under ASTM A 106, the minimum wall is .438". Therefore Dn/T = 12.75/.438 = 29.l.

(2) Enter 29.1 on the Dn/T axis of Figure 6.5.1 and move vertically to the intersection with the bending range boundary.

(3) Then move horizontally to determine the minimum recommended radius to diameter ratio which equals approximately 4.5. For practical purposes, bending radii are seldom expressed in terms of fractional numbers, but rather in terms of whole integers multiplied by the nominal pipe size. Hence, the recommended bending radius would be 5 x 12 = 60".

Example B: Determine the minimum permissible wall thickness required for induction bending 22" O.D. carbon steel pipe per ASTM A 53-Grade B at a 3D bend radius.

(1) Enter 3 on the R/Dn axis of figure 6.5.2 and move horizontally to the intersection with the bending range boundary.

(2) Then move verticality to determine the minimum recommended diameter to wall thickness ratio which equals approximately 45. i.e. Dn/tn = 45 or tn = Dn/45 = 22/45 = .489".

6.7 Figure 6.5.1 is based on extensive experience in furnace bending carbon and low alloy steel pipe. Since stainless and non-ferrous materials have higher coefficients of expansion than carbon and low alloy steels, a greater reduction in the density of the sand fill occurs as these materials are being heated to the bending temperature. As a result, the sand fill does not provide the same rigidity against flattening and buckling as it does when carbon or low alloy steel pipe is being bent. Because of this fundamental difference, special consideration must be given to the selection of the minimum bending radius by the design engineer.

6.8 Cold bending ranges can vary significantly with the process and degree of specialized tool used. Figure 6.8.1 can be used to select the type of bend or the process required.

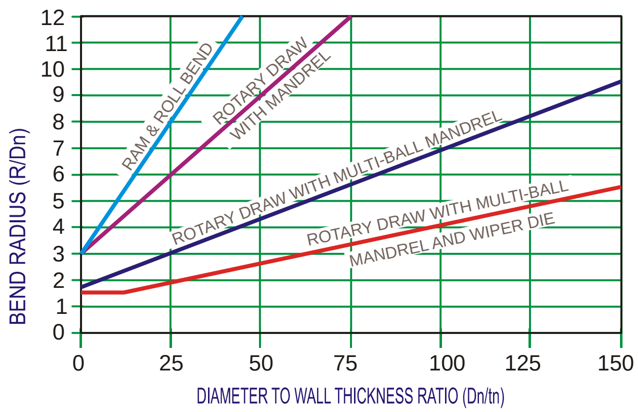


FIGURE 6.8.1
COLD BENDING RANGE

7. Material Allowances

7.1 The following recommendations for material allowances will vary with the bending method, material, pipe size, bend radius and the bend fabricator's equipment. It is suggested that the purchaser contact the fabricator for specific information.

7.2 To compensate for wall thinning from bending, the second column, ("Minimum Thickness Prior to Bending"), in Tables 7.2.1, 7.2.2, 7.2.3, and 7.2.4 can be used as a guide for ordering pipe for the appropriate process. ASME B31.1 Power Piping, equations 102.4.5(3B, 3C & 3E), and B31.3 Process Piping, equation 304.2.1(3c & 3e) define a minimum thickness at the extrados of the bend that is less than the minimum thickness required for straight pipe. Conversely, the minimum thickness for the intrados of the bend needs to be proportionally thicker than that required for straight pipe. The third column, ("Factored Thickness"), of these tables lists the minimum required thickness prior to bending factored for the allowable thinning at the extrados of the bend. Experience indicates that a minimum thickness of straight pipe shown in tables should be sufficient to meet the minimum thickness requirements after bending. Interpolation is permissible for bending to intermediate radii.

The code formula for calculating the minimum thickness required for the bend extrados, as defined in B31.1 2007 is:

$$t_m = \frac{PD_o}{2\left(\frac{SE}{I} + Py\right)} + A \quad \text{where} \quad I = \frac{4\left(\frac{R}{D_o}\right)+1}{4\left(\frac{R}{D_o}\right)+2}$$

The formula used to calculate the third column is:

$$(2^{nd}\text{ column value}) - (1 - \frac{t_m}{t}),$$

where t =Nominal pipe wall thickness minus manufacturing tolerance, and t_m is derived from equation (3) of B31.1, par. 104.1.2. The most conservative values over that range of pipe sizes and wall thicknesses where used.

TABLE 7.2.1
FURNACE BENDING

Bend Radius	Minimum Thickness Prior to Bending	Factored Thickness
6D	1.06 tm	1.03 tm
5D	1.08 tm	1.04 tm
4D	1.14 tm	1.09 tm
3D	1.25 tm	1.19 tm

TABLE 7.2.2
INDUCTION AND INCREMENTAL BENDING

Bend Radius	Minimum Thickness Prior to Bending	Factored Thickness
6Dn	1.06 tm	1.03 tm
5Dn	1.08 tm	1.04 tm
4Dn	1.10 tm	1.05 tm
3Dn	1.14 tm	1.08 tm
2Dn	1.22 tm	1.13 tm
1.5Dn	1.30 tm	1.19 tm

TABLE 7.2.3
ROTARY DRAW BENDING

Bend Radius	Minimum Thickness Prior to Bending	Factored Thickness
6Dn	1.09 tm	1.06 tm
5Dn	1.14 tm	1.10 tm
4Dn	1.20 tm	1.15 tm
3Dn	1.28 tm	1.22 tm

TABLE 7.2.4
RAM AND ROLL BENDING

Bend Radius	Minimum Thickness Prior to Bending	Factored Thickness
6Dn	1.08 tm	1.05 tm
5Dn	1.10 tm	1.06 tm
4Dn	1.13 tm	1.08 tm
3Dn	1.17 tm	1.11 tm

7.3 Since the start of the bend is somewhat dependent on factors not completely within the control of the bender, some additional length must be added to insure that overall center-to-end dimensions can be met. To compensate for this factor, the purchaser should add 6 inches to the total of the required straight tangent lengths.

7.4 Because induction heated bends are produced under pressure, a compression of the material takes place which results in more footage of straight pipe being required than that determined from the developed length. To provide for this compression the purchaser of induction bends should add 5% to the theoretical arc length. The compression of the material may leave a hump, or bump, at the beginning of the bend on the inside radius which is not detrimental to the bend.

Nominal pipe size	1" thru 2"	2½" thru 3½"	4" thru 48"
Pulling End	6"	8"	2D (10" min)
Holding End	6"	8"	1.5D (10" min)
Tangent Between Bends (Tm)	6"	9"	1D (12" min)*

*Note: 9" min for 4" pipe. 10" min for 5" pipe.

TABLE 7.5.1
MINIMUM TANGENT LENGTHS FOR FURNACE BENDS

7.5 In order to produce a bend properly, minimum straight tangents are required on both ends of the arc for holding and/or pulling purposes. Characteristic minimum tangent lengths for the various processes are given in Tables 7.5.1, 7.5.2, and 7.5.3. Definition of these tangent lengths can be seen in Figure 7.5.4. Minimum tangent lengths required for incremental bending should be obtained from the fabricator. Longer tangents should be utilized wherever possible and should be considered in the piping design. In cases where tangents must be kept short, it should be realized that an out-of-round condition may exist at the pipe ends.

Nominal Pipe Size	2" thru 24"	26" thru 66"
Front Tangent	OD+ 6"	OD+ 6"
Rear Tangent	72"	132"
Tangent Between Bends (Tm)	24"	60"

TABLE 7.5.2
MINIMUM TANGENT LENGTHS
FOR INDUCTION BENDING

Nominal Pipe Size	1" thru 10"
Front Tangent	2 X D
Rear Tangent	3 X D
Tangent Between Bends (Tm)	2 X D

TABLE 7.5.3
MINIMUM TANGENT LENGTHS FOR COLD BENDING

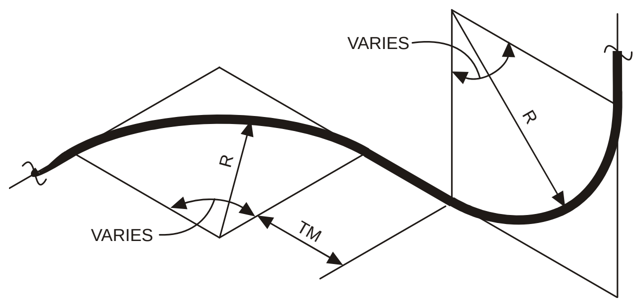


FIGURE 7.5.4
TANGENT LENGTHS

8. Material Requirements for Hot Bending

8.1 Pipe to be bent should be protected from the contamination of harmful materials such as the low melting temperature alloys of copper, brass and lead.

8.2 Stainless steel pipe suspected of being contaminated with ferrous metals or other harmful materials should be cleaned prior to bending to remove the contaminants.

8.3 Stainless steel pipe should be furnished in the solution annealed condition.

9. Ordering Information

9.1 The Pipe Bend Order Form, (Form 9.1), provides the recommended information required for the purchase pipe bends.

9.2 The applicability and acceptance criteria of each field, as defined by the Pipe Bend Order Form, shall be determined by the applicable codes, specifications and fabrication requirements.

9.3 Suggested Bending Tolerances:

Radius of Bend ---------------	1% of Dim “C”
Degree of Bend ---------------	0.5 Degree
Plane of Bend -----------------	1.0 Degree
Flat Plane of Bend------------	1% of Dim “C”
Linear Dimensions -----------	1/8”, 12” & under 3/16”, over 12”
Ovality in Bent Area ---------	8% of Diameter after Bend
Ovality at End Prep.----------	ASME B16.9

9.4 The miscellaneous remarks area and the space provided at the bottom of the pipe bend order form can be used to address additional requirements such as, Piece Marking, Centerline Scribing, Bend Heat Treatment, Butt Welds in Bends Area, etc.

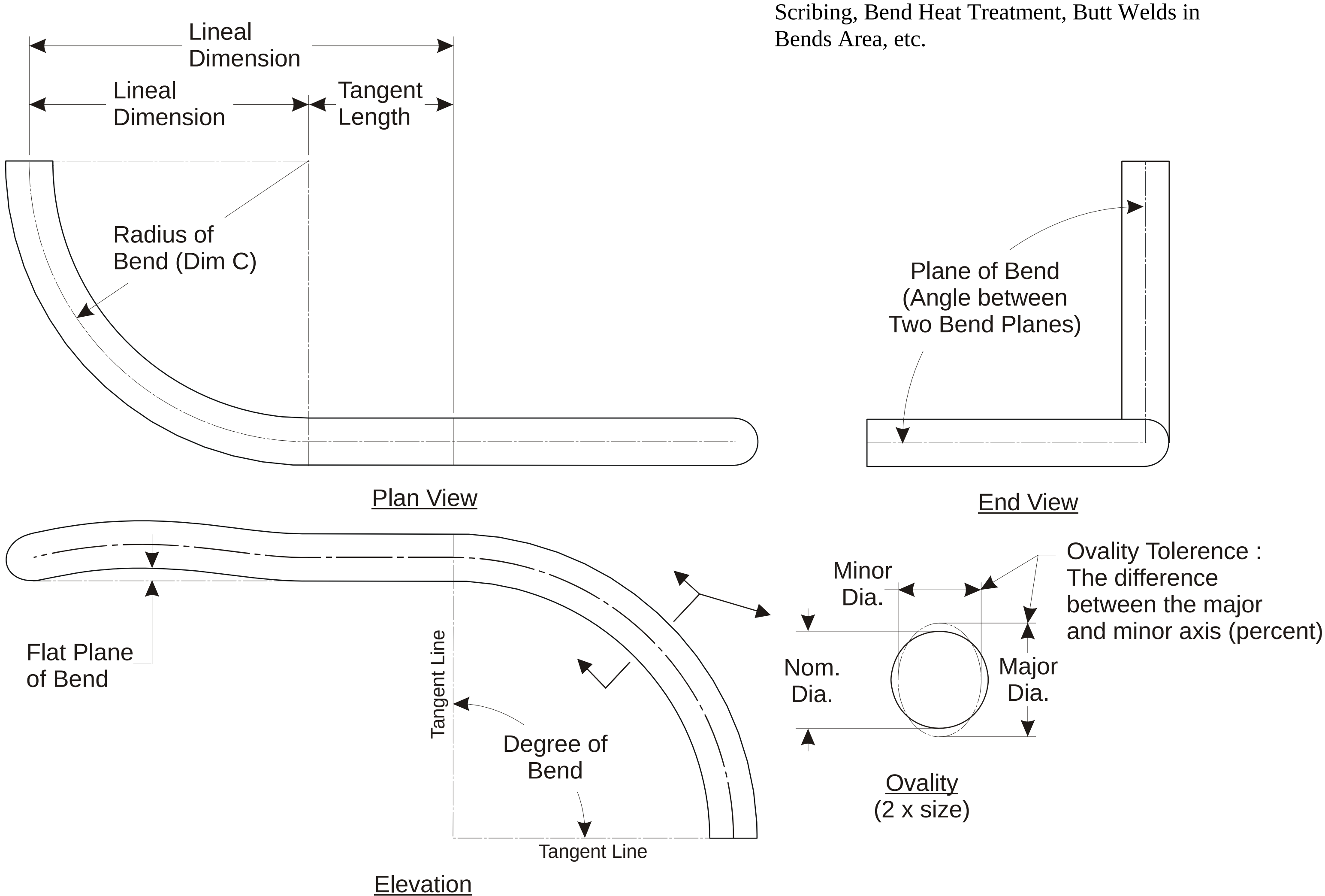


Figure 9.3
Tolerences

Pipe Bend Order Form

Pipe Fabrication institute

Pipe Bend Tag:	
Spool No.	
Material Spec:	
Pipe Diameter:	
Fab Code:	
Design Press:	
Design Temp:	
Corr. Allow:	
Calc'd Min Wall:	

Required Dimensions

"A" Tang Length	
"B" Tang Length	
Dimension C	
Angle D	
Dimension A	0.00
Dimension B	0.00
Dimension E	0.00

End Preperation

	B16.25 Sketch	Control "C"
"A" End:		n/a
"B" End:		n/a

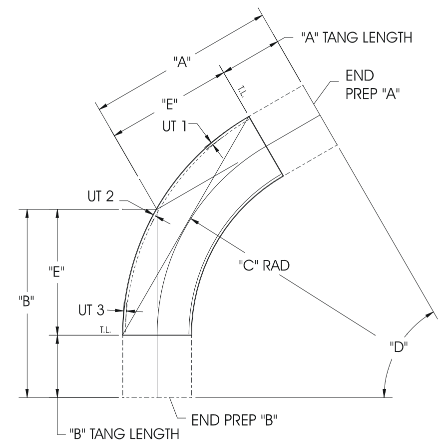
Req. Heat Treatment

Time	Per ASME B31.1 (129)
Temperature	Per ASME B31.1 (129)

Non Destructive Testing

MT/PT :	n/a
Hardness Tests:	n/a
Other:	

Bend shall be normalized and tempered after forming.



Tolerances

Radius of Bend:	1% of Dim "C"
Degree of Bend(D)	0.5 degrees
Plane of Bend (POB)	1.0 degrees
Flat Plane of Bend	1% of Dim "C"
Linear Dimensions	1/8"12" and under
	3/16" over 12"
Ovallity in Bent Area	8% of dia after Bending
Ovallity at End Prep	ASME B16.9

Misc Remarks

Circ welds shall not be located within pipe bend

Completed By Vendor

Actual Dimensions

Dimension A	
Dimension B	
Dimension C	
Angle D	

Min Thick as Measured

UT Point 1 :	
UT Point 2 :	
UT Point 3 :	

End Prep OD as Measured

	Major	Minor
End "A":		
End "B":		

Actual Heat Treatment

Time:	
Temperature:	
Remarks	

Actual Bending temp (P1 matl > 3/4" thk only)

Remarks	

Mat'l Heat No.

Date	Vendor Sign Off

Pipe Bend Tag:	

Bend shall be permanently die stamped and painted with Pipe Bend Tag No.
Bend must have the Centerlines of each run scribed in the pipe wall.

FORM 9.1
PIPE BEND ORDER FORM