CHAPTER A6

FABRICATION AND INSTALLATION OF PIPING SYSTEMS

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INTRODUCTION

Background

The term *fabrication* applies to the cutting, bending, forming, and welding of individual pipe components to each other and their subsequent heat treatment and nondestructive examination (NDE) to form a unit (piping subassembly) for installation.

The term *installation* refers to the physical placement of piping subassemblics, valves, and other specialty items in their required final location relative to pumps, heat exchangers, turbines, boilers, and other equipment; assembly thereto by welding or mechanical methods; final NDE; heat treatment; leak testing; and cleaning and flushing of the completed installation.

Depending on the economics of the particular situation, fabrication may be accomplished in a commercial pipe fabrication shop, or a site fabrication shop, where portions of the piping system are fabricated into subassemblies or modules for transfer to the location of the final installation.

Commercial pipe shops have specialized equipment for bending and heat treatment which is not normally available at installation sites. They also have certain types of automatic welding equipment which permits welding to be performed more efficiently and economically than in field locations where fixed position, manual arc welding is most often employed.

As a general rule piping NPS 2½ (DN 65) and larger for nuclear and fossil power plants, chemical plants, refineries, industrial plants, resource recovery, and cogeneration units are most often shop fabricated. Piping NPS 2 (DN 50) and smaller is often shop fabricated where special heat treatment or cleaning practices may be required; otherwise it is field fabricated. Pipelines and other systems involving long runs of essentially straight pipe sections welded together are usually field assembled.

In recent years, the infusion of new bending technologies, new welding processes, new alloys, fracture toughness limitations, and mandatory quality assurance (QA) programs have made piping fabrication and installation much more complex than in the past. Greater emphasis is being placed on written procedures for QA and quality control (QC) programs, special processes, and qualification and certification of procedures and personnel.

Improper selection of fabrication or installation practices can result in a system which will not function properly or will fail before its expected life span. Accordingly, fabrication and installation contractors must work closely with the designer and be aware of the mandatory requirements of the applicable codes, the unique requirements and limitations of the materials, and those of the fabrication and installation techniques being applied.

Codes and Standards Considerations

A great many codes and standards apply to piping. These are discussed in detail in Chap. A4.

It is incumbent on the fabricator and/or installer to be familiar with the details of these codes and standards since some codes have the force of law. As an example, the ASME B31.1 Power Piping Code[1] is referenced by ASME Section I Power Boilers[2] for piping classed as Boiler External Piping. The latter, which is law in most states and Canadian provinces, contains rules for code stamping, data reports, and third-party inspection. Piping under ASME Section III[3] also has legal standing. Most other piping codes are used for contractual agreements.

Most codes reference ASME Section V[4] for nondestructive examination methodology and ASME Section IX[5] for welding requirements.

Each of the codes covers a different piping application, and each has evolved in a different way over the years. For specific practices, some have mandatory requirements, while others only have recommendations. Heat treatment requirements may vary from one to another. The manner in which the code-writing bodies have perceived the hazardous nature of different applications has led to differing NDE requirements.

Generally, the codes are reasonably similar, but the owner, designer, fabricator, and installer must meet the specifics of the applicable code to ensure a satisfactory installation. It is essential that the designer be very familiar with the code being used and that purchasing specifications for material, fabrication, and installation be very specific. Reference to the code alone is not sufficient. In the design, a particular allowable stress for a specific material, grade, type, product form, and/or heat-treated condition was selected. The specifications issued for material purchase and fabrication must reflect these specifies to assure that the proper materials and fabrication practices are used.

As an example: Type 304 stainless steel has a specified carbon content of 0.08 percent maximum. There is no specified minimum. Footnotes in the B31.1 Code Allowable Stress Tables for Type 304 indicate that for use over 1000°F (538°C), the allowable stresses apply only when the carbon content is 0.04 percent or higher. It is essential that this requirement be put in the purchasing specification if the design temperature exceeds 1000°F (538°C).

Similarly, in the B31.1 Code, low chrome alloy electric fusion welded pipe has differing allowable stresses depending upon whether the plate from which it was made was annealed or normalized and tempered. If this material is to be heated above the lower critical temperature during fabrication by hot bending or forming, the designer should specify a postbending heat treatment appropriate for the allowable stress level used in the design.

It is also incumbent upon the fabricator and/or installer to be very familiar with the applicable code. Each project should be reviewed in detail. "Standard shop practices" may not always produce the desired result. Communication between the designer, fabricator, and installer is essential. All should be familiar with the various standards used in piping design. Most piping systems are composed of items which conform to some dimensional standards such as ASME B36.10M[6] and ASME B36.19M for pipe, B16.5[7] for flanges, etc. Other dimensional standards are issued by the Manufacturers Standardization Society (MSS)[8] and the American Petroleum Institute (API).[9]

The Pipe Fabrication Institute (PFI)[10] publishes a series of Engineering Standards which outline suggested practices for various fabrication processes. These standards give excellent guidance for many aspects of piping fabrication not covered by the codes.

The American Welding Society (AWS)[11] publishes a number of recommended practices for welding of pipe in various materials.

Materials Considerations

Piping systems are fabricated from a great variety of metals and nonmetals, material selection being a function of the environment and service conditions. Materials must conform to the standards and specifications outlined in the governing code. Some codes such as ASME Section III impose additional requirements on materials beyond those in the material specifications. All fabrication and installation practices applied to these materials must be conducted so as to assure that the final installation exhibits all of the properties implicit in the design. For example, hot bending of certain austenitic stainless steels in the sensitization range will reduce their corrosion resistance if they are not subsequently heat-treated. Accordingly, a heat treatment to restore these properties should be specified.

Consideration must also be given to the various types of piping products, their tolerances, alloys, heat-treated conditions, weldability, and formability. Pipe is made by a variety of processes and depending on the method of manufacture can have differing tolerances.

Most product forms also come in a variety of alloys, and the choice of a fabrication process may be governed by the alloy. ASME Section IX has developed a system of P Numbers and Group Numbers. This system groups material specifications by chemical composition and/or physical properties. Those with like compositions and properties are grouped together to minimize the number of welding procedure qualifications required. This method of grouping can also be applied to other fabrication processes as well.

FABRICATION

Drawings

Installation Drawings. Current industry practice is for the designer to prepare plans and sections or isometric drawings of the required piping system. These, together with line specifications, outline all the requirements needed for the fabrication and installation. Usually the weld bevel requirements for field welds are specified to assure compatibility between all the system components to be field welded.

Frequently the shop welding bevels are left to the discretion of the fabricator, provided, of course, the required weld quality is attainable.

Location and numbers of field welds are an economic consideration of available pipe lengths, shipping or heat-treating limitations, and field installation limitations.

Shop Details. A piping system prefabricated at a commercial pipe fabrication shop is usually divided into subassemblies or spools.

The manner in which a system is divided depends on many factors: available lengths of straight pipe, dimensional and weight limitations for shipping and heat treatment, field welding clearance requirements, and sometimes scheduling needs.

Bending, forging, special heat treatment, cleaning, and as much welding as possible are normally performed in the shop. Every attempt is made to minimize the number of field welds, but this must be balanced economically against the added costs of transportation and greater field rigging problems because of larger, heavier, more complex assemblies. Where the site conditions are adverse to normal field erection practices, much of the plant can be fabricated in modules for minimal onsite installation work. Once the number and locations of field welds have been decided, the fabricator will prepare detailed drawings of each subassembly.

Each subassembly drawing will show the required configuration; all necessary dimensions required for fabrication; reference to auxiliary drawings or sketches; size, wall thickness, length, alloy, and identification of the materials required; code and classification; reference to special forming, welding, heat treatment, NDE, and cleaning requirements; need for third-party inspection; weight and piece identification number. See Fig. A6.1.

Tolerances. In order to assure installation of a system within a reasonable degree of accuracy, all the components involved must be fabricated to some set of tolerances on those dimensions which affect the system length. Tolerances on valve dimensions are given in B16.34,[12] those of welding fittings in B16.9,[13] and those for flanges and flanged fittings in B16.5, B16.1,[14] etc. The assembly of these components will result in ‘‘tolerance stack-up,’’ which could have a significant impact on the overall dimensions, particularly in a closely coupled system.

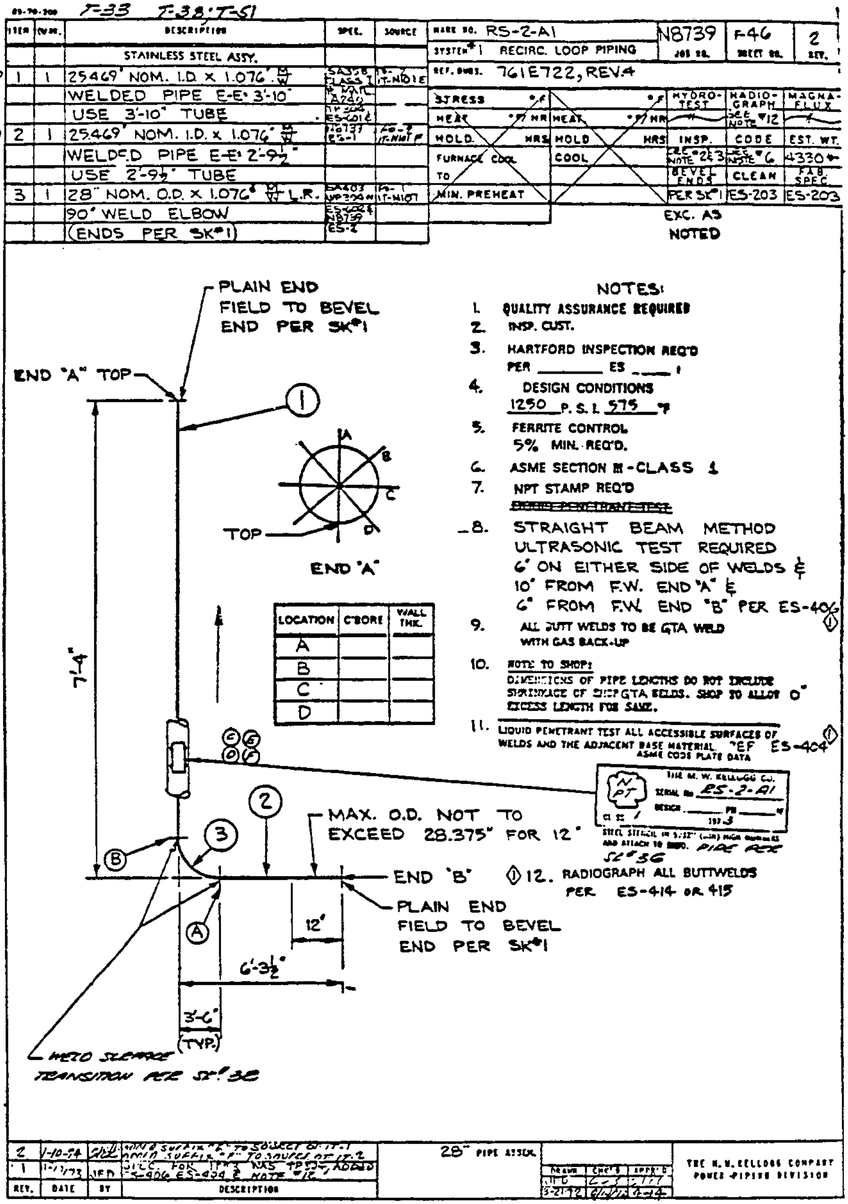
Piping subassembly tolerances normally conform to PFI-ES-3 ‘‘Fabricating Tolerances.’’[15] Usually the terminal dimensions are held to ±⅛ in, but can be held more closely upon agreement with the fabricator.

In order to assure that tolerance stack-up is held to a minimum, the manner in which shop details are dimensioned should be carefully studied. As an example, assemblies with multiple nozzles can result in large deviations if these are dimensioned center to center. A better way is to select a base point and dimension all nozzles from this location. This assures that all nozzles are ±⅛ in (3.0 mm) from the base point. See Fig. A6.2.

For angle bends, terminal dimensions and often a chord dimension are required, since a small variation in angle with long ends can result in serious misalignment. See Fig. A6.3.

Sometimes assemblies which have been fabricated within tolerance may not fit in the field because of tolerance stack-ups on equipment to which they are attached. This will be addressed in the section, ‘‘Installation.’’

Procedures and Travelers. The need to assure better control of fabrication processes has led the use of written procedures for most operations. Fabricators will have a library of written procedures controlling cutting, welding, bending, heat treatment, nondestructive examination, and testing. Welding procedures in most



T-33 T-38; T-51

ITEM	QUAN.	DESCRIPTION	SPEC.	SOURCE
		STAINLESS STEEL ASSY.		
1	1	25.469" NOM. I.D. x 1.076" MIN. W	SA358 CLASS I	10-? IT-NOTE
		WELDED PIPE E-E: 3'-10"	& MAT'L A240	—
		USE 3'-10" TUBE	TP304 ES-201&	
2	1	25.469" NOM. I.D. x 1.076" MIN. W	[illegible] ES-1	10-2 IT-NOTE F
		WELDED PIPE E-E: 2'-9½"		
		USE 2'-9½" TUBE		
3	1	28" NOM. O.D. x 1.076" MIN. W L.R.	SA403 WP304 W	10-1 IT-NOTE
		90° WELD ELBOW	ES-402& N8739	
		(ENDS PER SK#1)	ES-2	

MARK NO. RS-2-A1

SYSTEM #1 RECIRC. LOOP PIPING

JOB NO. N8739

SHEET NO. F-46

REV. 2

REF. DWGS. 761E722, REV.4

STRESS °F	°F	HYDRO-TEST	RADIO-GRAPH	MAGNA-FLUX
HEAT °F/HR	HEAT °F/HR	—	SEE NOTE #12	—
HOLD HRS	HOLD HRS	INSP.	CODE	EST. WT.
FURNACE COOL TO	COOL	SEE NOTE #2&3	SEE NOTE #6	4330#
		BEVEL ENDS	CLEAN	FAB. SPEC.
MIN. PREHEAT		PER SK#1	ES-203	ES-203

EXC. AS NOTED

NOTES:

1. QUALITY ASSURANCE REQUIRED
2. INSP. CUST.
3. HARTFORD INSPECTION REQ'D PER ______ ES ____
4. DESIGN CONDITIONS 1250 P.S.I. 575 °F
5. FERRITE CONTROL 5% MIN. REQ'D.
6. ASME SECTION III-CLASS 1
7. NPT STAMP REQ'D ~~[illegible] PENETRANT TEST~~
8. STRAIGHT BEAM METHOD ULTRASONIC TEST REQUIRED 6" ON EITHER SIDE OF WELDS & 10" FROM F.W. END "A" & 6" FROM F.W. END "B" PER ES-406 ①
9. ALL BUTT WELDS TO BE GTA WELD WITH GAS BACK-UP
10. NOTE TO SHOP: DIMENSIONS OF PIPE LENGTHS DO NOT INCLUDE SHRINKAGE OF SHOP GTA WELDS. SHOP TO ALLOW 0" EXCESS LENGTH FOR SAME.
11. LIQUID PENETRANT TEST ALL ACCESSIBLE SURFACES OF WELDS AND THE ADJACENT BASE MATERIAL. REF ES-404 ①
12. ① RADIOGRAPH ALL BUTTWELDS PER ES-414 OR 415

LOCATION	C'BORE	WALL THK.
A		
B		
C		
D		

ASME CODE PLATE DATA

THE M. W. KELLOGG CO.
SERIAL No. RS-2-A1
DESIGN ____ PSI ____ °F
CL. No. 1
197 3

STEEL STENCIL IN 5/32" HIGH NUMBERS AND ATTACH TO [illegible]. PIPE PER SK#36

REV.	DATE	BY	DESCRIPTION
2	1-10-74	[illegible]	ADDED SUFFIX "E" TO SOURCE OF IT-1 ADDED SUFFIX "F" TO SOURCE OF IT-2
1	1-?/73	JFD	DISC. FOR IT#3 WAS TP304, ADDED ES-406, ES-404 & NOTE #12

28" PIPE ASSEM.

DRAWN	CHK'D	APPR'D
JFD	[illegible]	[illegible]
3-21-72	[illegible]	[illegible]

THE M. W. KELLOGG COMPANY
POWER PIPING DIVISION

FIGURE A6.1 Shop detail. (*Pullman Power Products Corporation*)

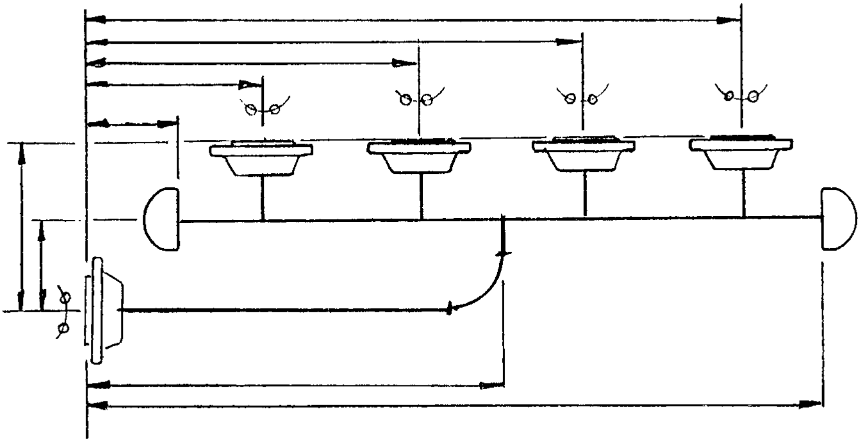


FIGURE A6.2 Dimensioning.

codes are qualified under ASME Section IX, which requires written Welding Procedure Specifications (WPSs) backed up by Procedure Qualification Records (PQRs). Similarly ASME Section V requires NDE to be performed to written procedures.

Frequently, piping fabricators use a system of travelers to control flow through the shop. This practice is well-suited to fabrication of piping subassemblies under QA or QC programs, where record keeping is required. It also affords the purchaser and the third-party inspector opportunities for establishing "hold points" where they may wish to witness certain operations or review certain records.

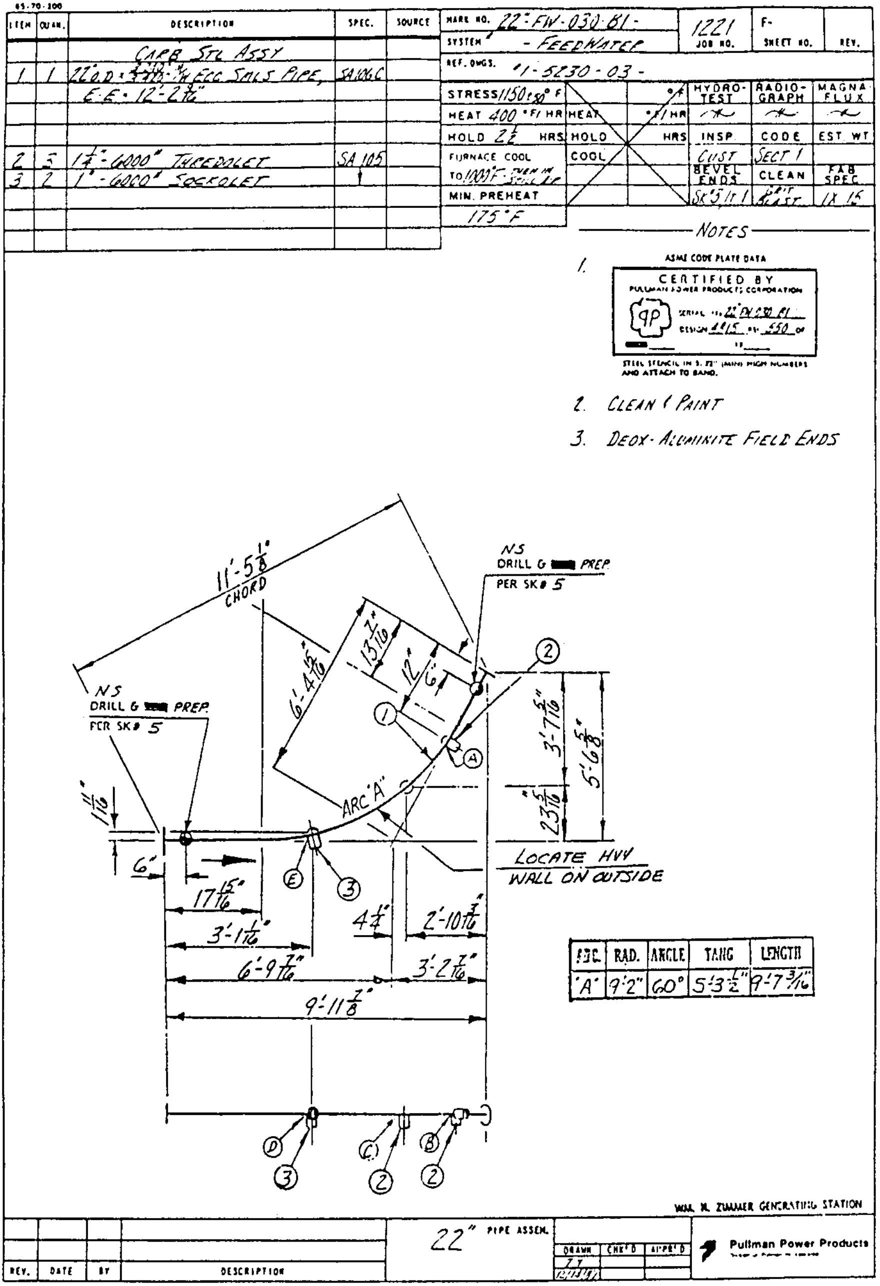
Fabrication Practices

Cutting and Beveling. The methods of cutting plate or pipe to length can be classed as mechanical or thermal.

Mechanical methods involve the use of saws, abrasive discs, lathes, and pipe-cutting machines or tools. See Fig. A6.4.

Thermal methods are oxyfuel gas cutting or electric arc cutting. Oxyfuel gas cutting is a process wherein severing of the metal is effected by the chemical reaction of the base metal with oxygen at an elevated temperature. In the cutting torch, a fuel such as acetylene, propane, or natural gas is used to preheat the base metal to cutting temperature. A high-velocity stream of oxygen is then directed at the heated area resulting in an exothermic reaction and severing of the material. Oxyfuel gas cutting is widely used for cutting carbon steels and low alloys. It does, however, lose its effectiveness with increasing alloy content.

For higher alloy materials, some form of arc cutting is required. Plasma arc cutting is the process most frequently employed. It involves an extremely high temperature (30,000 to 50,000°K), a constricted arc, and a high-velocity gas. The torch generates an arc which is forced to pass through a small-diameter orifice and concentrate its energy on a small area to melt the metal. At the same time a gas such as argon, hydrogen, or a nitrogen-hydrogen mixture is also introduced at the orifice where it expands and is accelerated through the orifice. The melted metal is removed by the jetlike action of the gas stream.



65-70-100

ITEM	QUAN.	DESCRIPTION	SPEC.	SOURCE
		CARB STL ASSY		
1	1	22"O.D. x [illegible] ECC SMLS PIPE,	SA106C	
		E.E. 12'-2 7/16"		
2	5	1 1/4" - 6000# THREDOLET	SA 105	
3	2	1" - 6000# SOCKOLET	↑	

MARK NO. 22"-FW-030-B1-

SYSTEM - FEEDWATER

1221 JOB NO.

F- SHEET NO.

REV.

REF. DWGS. #1-5230-03-

STRESS 1150±50 °F		°F	HYDRO-TEST	RADIO-GRAPH	MAGNA FLUX
HEAT 400 °F/HR	HEAT	°F/HR	—	—	—
HOLD 2 1/2 HRS	HOLD	HRS	INSP.	CODE	EST. WT
FURNACE COOL	COOL		CUST	SECT 1	
TO 1000°F · THEN IN STILL AIR			BEVEL ENDS	CLEAN	FAB SPEC
MIN. PREHEAT			SK 5 IT 1	GRIT BLAST	IX 15
175 °F					

NOTES

1. ASME CODE PLATE DATA

CERTIFIED BY
PULLMAN POWER PRODUCTS CORPORATION
SERIAL NO. 22"FW-030-B1
DESIGN 1115 PSI 550 °F
[illegible] ______ 19 ______

STEEL STENCIL IN 3/8" (MIN) HIGH NUMBERS AND ATTACH TO BAND.

2. CLEAN & PAINT

3. DEOX-ALUMINITE FIELD ENDS

ARC	RAD.	ANGLE	TANG	LENGTH
'A'	9'-2"	60°	5'-3 1/2"	9'-7 3/16"

WM. H. ZIMMER GENERATING STATION

22" PIPE ASSEM.

DRAWN	CHK'D	APPR'D
J.J.		
12/13/71		

REV.	DATE	BY	DESCRIPTION

Pullman Power Products

FIGURE A6.3 Dimensioning a bend. (*Pullman Power Products Corporation*)

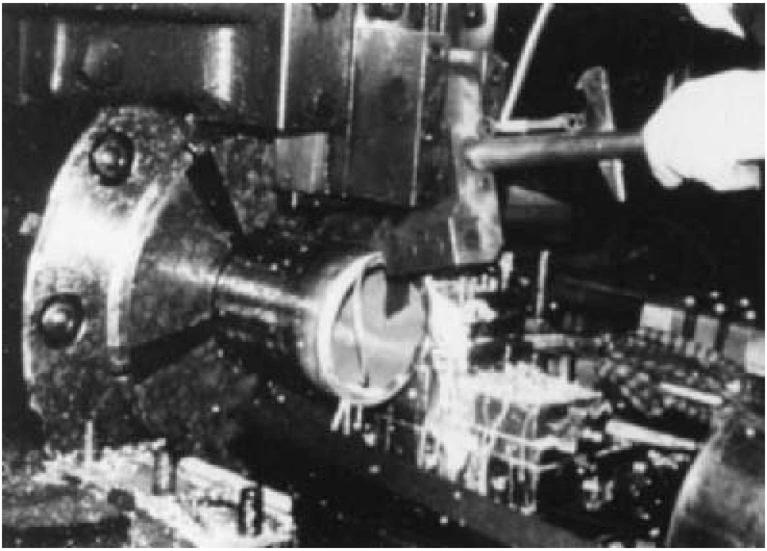


FIGURE A6.4 Pipe-cutting machine. (*Pullman Power Products Corporation*)

Because oxyfuel gas and arc cutting involve the application of heat, preheating may be advisable in some cases.

A very detailed description of oxyfuel gas and arc cutting is presented in *The Welding Handbook.*[16]

Weld end bevels can also be prepared by the mechanical or thermal methods just described. Both mechanical and thermal methods are used to apply the V bevel, which is used in the vast majority of piping applications. For compound and U bevels or those which may involve a counterboring requirement, horizontal boring mills are most appropriate. Various factors to be considered in selecting a weld end bevel are discussed in the section, ''Welding Joint Design.''

Forming. The term *forming* as it relates to piping fabrication encompasses bending, extruding, swaging, lapping, and expanding. All of these operations entail the use of equipment normally only available in pipe fabrication shops. Although the availability of welding fittings in the form of elbows, tees, reducers, and lapped-joint stub ends may reduce the need for certain of these operations, economics may dictate their use, especially where special pipe sizes are involved.

Bending

Economics. The use of bends versus welding fittings for changes in direction should be carefully evaluated from an economic viewpoint. Bends whose radii range from 3 to 5 times the nominal pipe diameter will offer the least pressure drop while still affording adequate flexibility to the system. Since each bend eliminates a welding fitting and at least one weld with its attendant examination, bending is very often the economic choice. In the case of special pipe sizes which are frequently used for main steam, reheat, and feedwater lines in large central power generating units, bending may be the only option available.

Limitations. The metal being bent should preferably exhibit good ductility and a low rate of strain hardening. Most metals used in piping systems fulfill these requirements. A successful bend is also a function of its diameter, thickness, and bending radius. As the diameter-to-thickness ratio increases and the bending radius decreases, there is greater probability of flattening and buckling. Each bending process has differing capabilities, so the selection of a bending process rests on the availability of equipment and/or practices capable of handling the material, diameter, thickness, and bending radius involved.

Accept and Reject Criteria. The codes have certain requirements for the acceptability of finished bends:

1. *Thinning:* In every bending operation the outer portion of the bend (extrados) stretches and the inner portion (intrados) compresses. This results in a thinning of the extrados and a thickening of the intrados. Because of uncertainties introduced by the pipe-manufacturing method, by the pipe tolerances, and by those introduced by the pipe-bending operation itself, it is not possible to exactly predetermine the degree of thinning. However, it can be approximated by multiplying the thickness before bending by the ratio:

$$\frac{R}{R+r} \tag{A6.1}$$

where r = the radius of the pipe (½ the outside diameter)
R = the radius of the bend

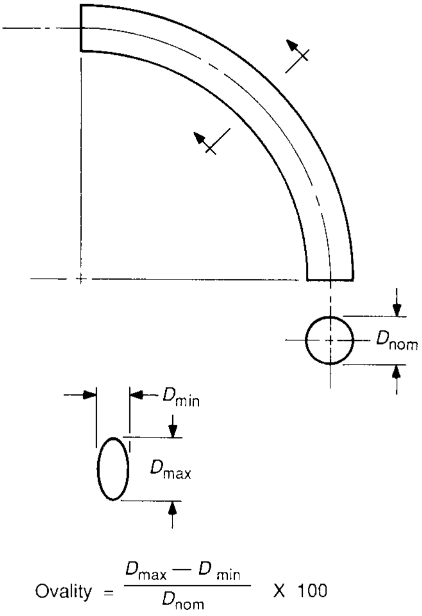


FIGURE A6.5 Bend ovality.

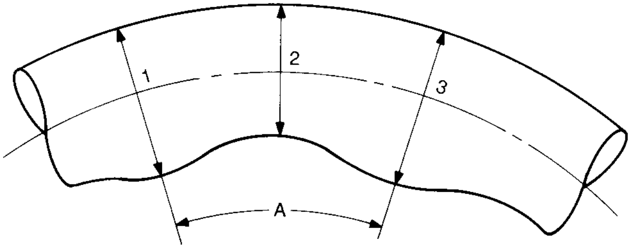
The codes require that the wall thickness at the extrados after bending be at least equal to the minimum wall thickness required for straight pipe. Accordingly, the fabricator must assure that the wall thickness ordered has sufficient margin for this effect.

Although the codes do not comment on the resulting increased thickness of the intrados, this thickness does serve to offset a portion of the increased stresses caused by internal pressure which are found at this location. (See *Theory and Design of Modern Pressure Vessels.*[17])

2. *Ovality:* A second acceptance criteria is ovality. During the bending operation, the cross section of the bend arc frequently assumes an oval shape whose major axis is perpendicular to the plane of the bend. See Fig. A6.5. The degree of ovality is determined by the difference between the major and minor axes divided by the nominal diameter of the pipe.

Where the bend is subject to internal pressure, the pressure tries to reround the cross section by creating secondary stresses in the hoop direction. Some codes consider an ovality of 8 percent acceptable in this case. Where the bend is subject to external pressure, the pressure tries to collapse the cross section. The ASME B31.3 Code[18] recommends a 3 percent maximum ovality when the bend is subject to external pressure.

3. *Buckling:* Bending of pipe with large diameter-to-thickness ratios often results in buckling rather than thickening of the intrados, even where internal mandrels or other devices are employed to minimize it. The codes do not address this subject. It is, however, often the subject of "good workmanship" debates. The PFI gives a criterion which has been generally accepted. This appears in PFI ES-24.[19] An acceptable buckle is one where the ratio of the distance between two crests divided by the depth of the average crest to valley is equal to or greater than 12. See Fig. A6.6



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.

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

Ratio of the distance between crests to depth must be equal to or greater than 12.

$$\frac{A}{\text{Depth}} \geq \frac{12}{1}$$

FIGURE A6.6 Suggested pipe buckling tolerance. (*Pipe Fabrication Institute PFI ES-24*)

Bending Methods. Pipe is bent by a variety of methods, using bending tables or bending machines, with and without the application of heat. The selection of one method over another is a function of economics, materials properties, pipe size, bending radius, and equipment availability. The arc length of the bend may be heated in order to reduce the yield strength of the material. Higher bending temperatures result in lowering the yield strength and reduction of the bending energy required.

Cold bending normally infers bending at ambient temperature, while hot bending infers the application of heat. However, definitions given in B31.1 and ASME Section III create an exception to this for *ferritic* materials. These codes define cold bending of *ferritic* steels as any operation where the bending is performed at a temperature 100°F (55°C) below the lower critical or lower. Ferritic materials undergo a phase change on heating and cooling. On heating, this change starts at a temperature called the *lower critical.* (See *Heat Treatment—Ferritic Steels*).

Ferrous Pipe and Tubes

1. *Cold bending:* Where sufficient quantities of repetitive bends are required, ferrous pipes and tubes up to NPS 10 or 12 (DN 250 or 300) with wall thickness of ½ in (12.7 mm) or less are most often bent at ambient temperature using some type of bending machine.

There are a great variety of cold bending machines available, with degrees of sophistication varying from simple manually operated single-plane bending devices to numerically controlled hydraulically operated machines capable of multiplane bends.

In ram-type bending, two pressure dies which are free to rotate are mounted in a fixed position on the machine frame. The pipe to be bent is positioned against these dies. A ram then presses a forming die against the pipe and the pressure dies wipe the pipe around the forming die. See Fig. A6.7. Ram bending is usually applied to heavier wall thicknesses.

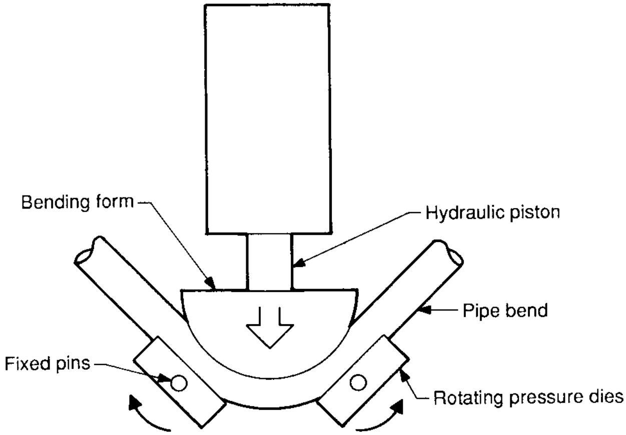


FIGURE A6.7 Ram bender.

In compression bending the pipe is clamped to a stationary bending die and wiped around it by a follower. As in all bends, the extrados thins and the intrados thickens or compresses. The degree of compression is greater than the thinning in this method. Compression bending is usually limited to heavier walls and larger bending radii. See Fig. A6.8 to compare compression and draw bending.

In rotary draw bending the pipe is clamped to a rotating bending form and drawn past a pressure die which is usually fixed. See Fig. A6.9. The degree of thinning of the extrados is greater than the compression of the intrados. This method permits bending of thinner wall pipe and tubes at smaller bending radii. To accommodate lighter walls and tighter radii it is often advisable to provide internal support to minimize flattening or buckling. Usually this takes the form of an internal mandrel. As the diameter-to-thickness ratio increases and the bending radius decreases, mandrels using follower balls are employed. See Fig. A6.10.

Roll bending is often used for coiling. One of its great advantages is that the bending radius is not dependent on a fixed radius die, and consequently there is great flexibility in choosing a bending radius. In roll bending three power-driven rolls, usually in pyramid form, are used. The pipe to be bent is placed between the

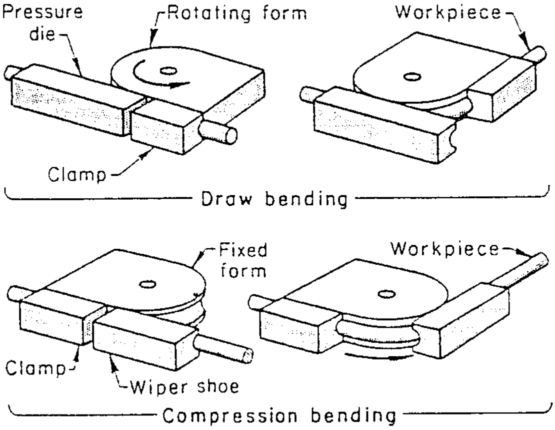


FIGURE A6.8 Comparison of the essential elements of draw bending and compression bending. (*Metals Handbook*[20])

two lower rolls and the upper roll. Bending is accomplished by adjusting the rolls relative to each other as necessary to attain the required diameter. See Fig. A6.11.

Pipe can also be cold bent on a bending table in the manner described for hot bending below, except that for ferritic materials the bending temperature is kept at least 100°F (56°C) below the lower critical.

A postbending heat treatment for cold bends may be advisable for some alloys, degree of deformation, certain service conditions, or when mandated by code.

2. *Hot bending:* In those cases where suitable cold bending equipment is unavail-

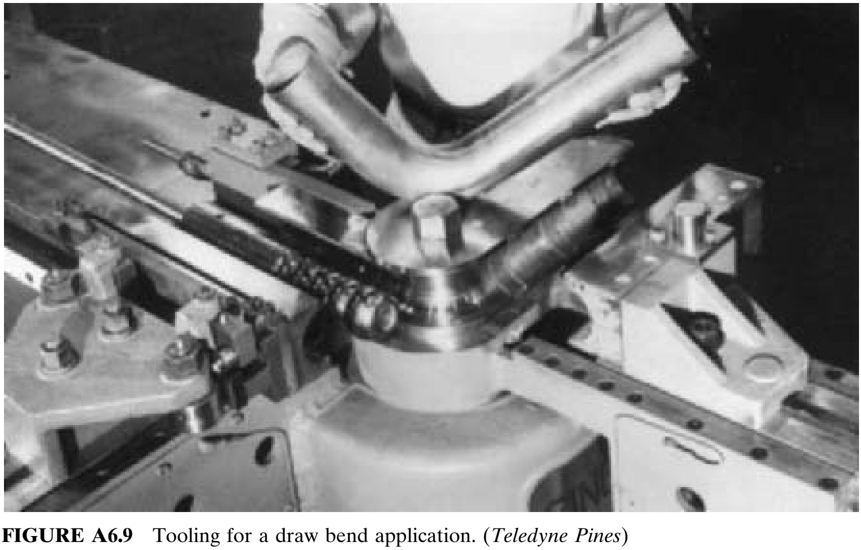


FIGURE A6.9 Tooling for a draw bend application. (*Teledyne Pines*)

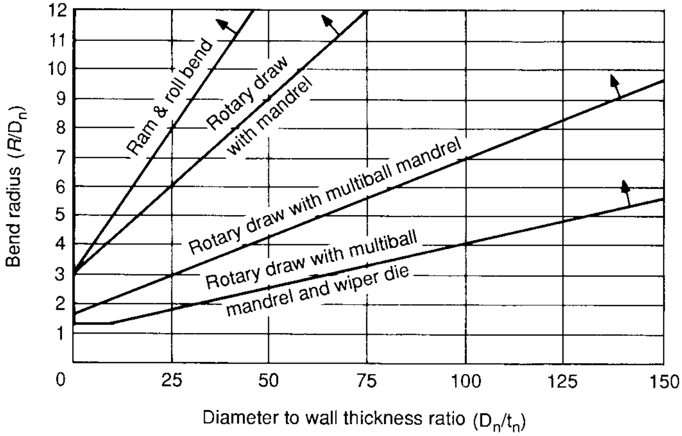


FIGURE A6.10 Cold bending ranges. (*Pipe Fabrication Institute PFI ES-24)*

able, hot bending may be employed. For hot bending of ferrous materials the pipe to be bent is usually heated to temperatures in the range of 1750 to 2050°F (954 to 1121°C). For austenitic materials these temperatures may introduce sensitization, and for ferritic materials they will exceed the critical temperature where metallurgical phase changes occur. See the section "Heat Treatment" for a discussion of these subjects.

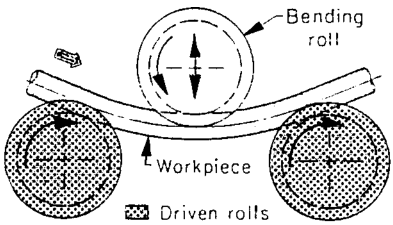


FIGURE A6.11 Operating essentials in one method of three-roll bending. (*Metals Handbook*[20])

The traditional method of hot bending is performed on a bending table. Depending on the diameter-to-thickness ratio, the pipe to be bent may be packed with sand to provide more rigidity and thus reduce the tendency for buckling. A rule of thumb is to sand fill if the diameter-to-thickness ratio is 10 to 1 or greater for 5-diameter bends. However, when the diameter-to-thickness ratio approaches 30 to 1, sand begins to lose its effectiveness, and buckles will appear. As the diameter of the pipe increases, the probability of buckling will increase since the sand fill will not expand in proportion to the pipe, leaving a void between the pipe and packing. It becomes pronounced around NPS 24 (DN 600).

After the pipe has been packed with sand, it is placed in a specially designed bending furnace. The furnace is usually gas fired through ports along its length, placed to direct the flames around the pipe and avoid direct flame impingement. The furnace is controlled by thermocouples or pyrometers to assure that the required bending temperature is attained but not exceeded. Depending on the length of arc to be bent, it may be necessary to make the bend in more than one heat.

After the segment to be bent has attained the required temperature throughout its thickness, the pipe is placed on the bending table. One end is restrained by holding pins and the other is pulled around by block and tackle powered by a winch. As bending progresses, the arc is checked against a bending template. Reposi-

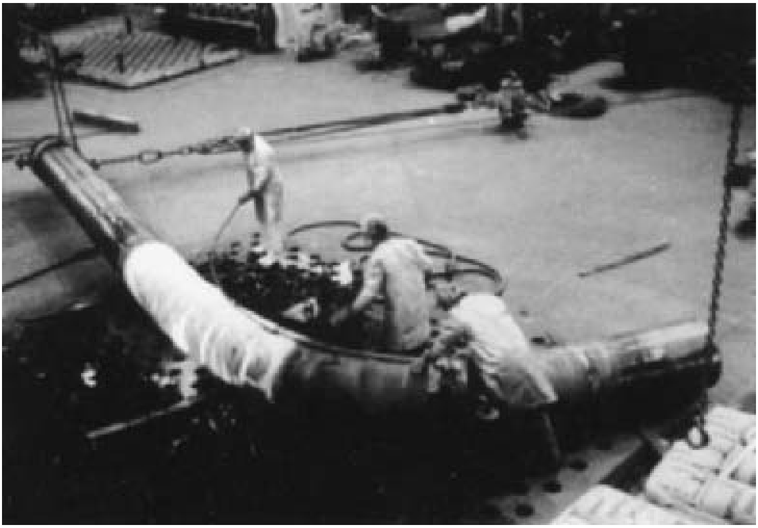


FIGURE A6.12 Hot bending on a table. (*Pullman Power Products Corporation*)

tioning of the holding pins may be necessary. See Fig. A6.12. For ferritic steels, it is recommended that the bending be completed above the upper critical temperature of the metal, usually about 1600 to 1725°F (870 to 940°C).

There are certain limits as to the combination of diameters, thicknesses, and bending radii which can be accommodated by the hot table bend method. PFI Standard ES-24 contains a chart of suggested limits for bend radius versus diameter to wall thickness ratios. See Fig. A6.13.

To fulfill the need for a bending process beyond the capabilities of hot table bending, the M. W. Kellogg Co. developed the increment bending process, which was further refined by Pullman Power Products Corp. In this process, one end of the pipe is fixed in an anchor box while a clamp connected to a hydraulic piston is attached to the other. A gas torch ring burner assembly is positioned at one end of the arc to be bent. The burner assembly is sized to heat a length of arc (increment) about 1 to 2 times the pipe wall thickness. The increment length is selected to be less than the buckling wave length of the pipe. The increment is then heated to bending temperature. Optical pyrometers are used to control the heating to assure that proper temperature is attained but not exceeded. At bending temperature the hydraulic piston pulls the clamped end a fixed amount to bend the heated increment. The increment is then water cooled, the torch ring moved to the next increment, and the process is repeated. As many as 350 increments may be required for a typical NPS 24 × ⅜-in (DN 600 × 9.5 mm), 90°, 5-diameter bend.

The process can produce bends in sizes from NPS 8 to 48 (DN 200 to 1200) with bending radii of 3 pipe diameters and larger in ferrous and nickel-alloy materials. Because the heat is applied from one side only, thicknesses are limited to 2 in (50 mm) and less.

In more recent years a more sophisticated piece of bending equipment has entered the pipe-bending field, notably the Induction Bender. In this process the increment to be bent is heated by an induction coil, and the bending operation is continuous. The pipe to be bent is inserted in the machine, and the start of the arc

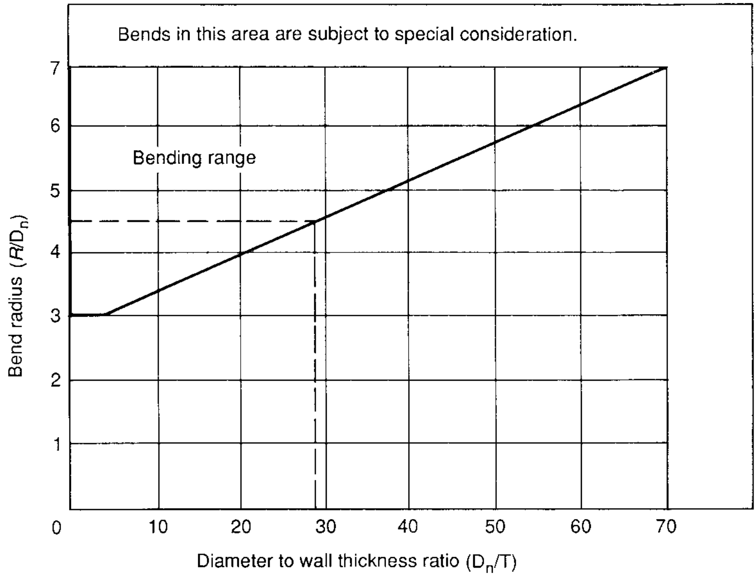


FIGURE A6.13 Limits for hot bending on a table. *(Pipe Fabrication Institute PFI ES-24)*

is positioned under the induction coil. The portion of the pipe upstream of the coil is clamped to a rotating arm fixed to the required bend radius. The downstream portion of the pipe is pushed hydraulically through the coil, where it attains bending temperature. Since it is clamped to the rotating arm, a bending moment is imposed on the pipe and it bends as it moves through the coil. As soon as it has been bent, the heated section is cooled to restore its prior rigidity. The permissible rate of cooling is a function of material composition. Low-carbon steels and some low Cr molys may be water quenched. It is recommended that the 9Cr-1Mo-V material be cooled in still air.

The Induction Bender is manufactured in several sizes depending on the expected combinations of pipe size and bending radius. These range from NPS 3½ to 64 (DN 80 to 1600) and from 8 to 400 in (DN 200 to 10,000 mm) in radius. Since induction is used as the heating method, wall thicknesses as heavy as 4 in (100 mm) can be bent. (See Fig. A6.14a and 6.14b.)

3. *Nonferrous pipe and tubes:* Although most of the equipment used to bend ferrous materials is also used for bending nonferrous materials, the details of bending do differ from those for ferrous materials and also vary between the several nonferrous materials themselves. Accordingly, it is wise to obtain specific procedural information from the materials' producers or from other reliable sources such as the latest edition of *The Metals Handbook.*[20] Certain nonferrous materials can be hot bent.

Aluminum and aluminum alloys can be bent cold using the same types of bending equipment used for ferrous materials. Alloys in the annealed condition are easiest to bend, but care is required in selecting tooling because of the low tensile strength and high ductility of these materials. Alloys with higher tempers and heat-treatable alloys require larger bending radii for satisfactory results. It is seldom necessary to

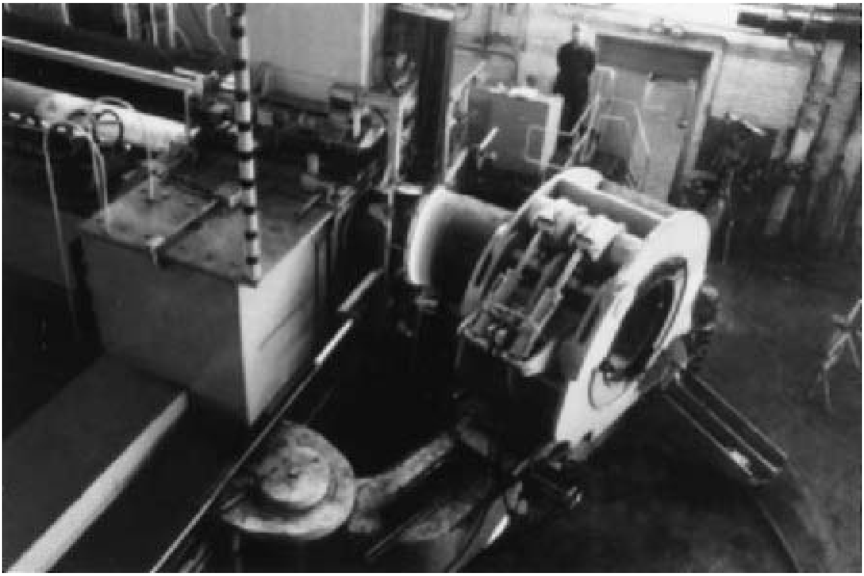


FIGURE A6.14a Induction bending. (*BendTec, Inc.*)

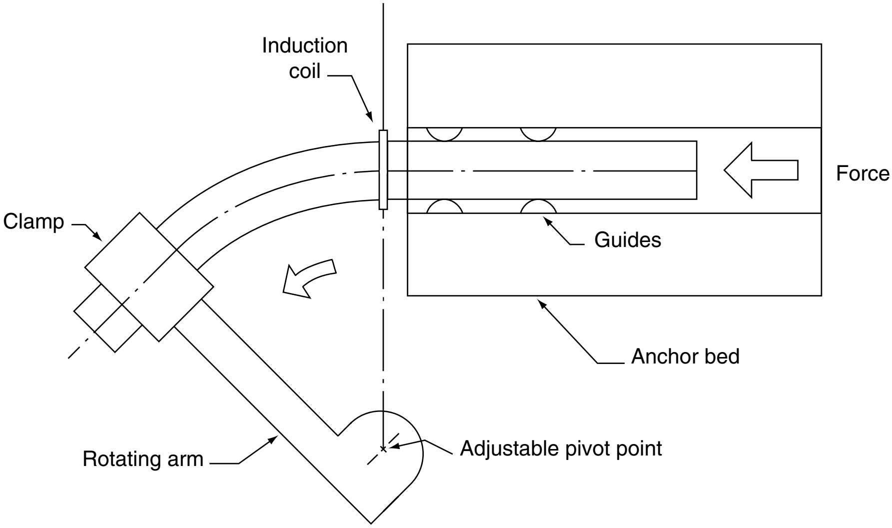


FIGURE A6.14b Induction bender.

TABLE A6.1 Temperature Range for Hot Bending of Copper and Copper Alloy Pipe and Tube

Material	Spec no.	Alloy	Temperature range (°F)
Copper deoxidized	SB-42, SB-75	C10200	1400–1600
Red brass	SB-43, SB-135	C23000	1450–1650
Copper silicon A	SB-315	C65500	1300–1600
70-30 CuNi	SB-466, SB-467	C71500	1700–2000
80-20 CuNi	SB-466	C71000	1600–1900
90-10 CuNi	SB-466, SB-467	C70600	1400–1800

Source: Adapted from ASME Boiler & Pressure Vessel Code 1995 ed., Section VIII Div. 1 Table NF-4.

heat aluminum for bending: however, non-heat-treated materials can be heated to 375°F (190°C) with minimal loss of properties, Heat-treated alloys require specific time-temperature control. More detailed information is available from the manufacturers of aluminum products.

Copper and copper alloy pipe and tube can be readily bent to relatively small radii. Although copper can be bent hot, the vast majority is done cold. For draw bending an internal mandrel is required and for other methods internal support is recommended. For very tight radii a snug-fitting forming block and shoe which practically surround the pipe at the point of bending are needed to preclude buckling.

Hot bending of copper and copper alloys particularly in larger diameters and walls is common. Pipes are usually sand-filled, and contoured bending dies are recommended. See Table A6.1. More information can be obtained from the Copper Development Association.[21]

Nickel and nickel-alloy pipe can be cold bent with the same type of bending equipment used for ferrous materials. Use of material in the annealed condition is preferred. For bends with radii 6 diameters and less, filler material or internal mandrels are required. Draw bending with internal mandrels is the preferred method for close-radius bending. Galling can become a problem, and chromium-plated or hard bronze-alloy mandrels should be used.

Nickel and nickel alloys can be hot bent using the same practices as for ferrous steels. Sand filling is appropriate. Care should be taken to assure that the sand and heating fuel are low in sulfur and that any marking paints or crayons or lubricants have been removed. These materials can be bent over a wide temperature range. See Table A6.2. The best bending is usually between 1850 and 2100°F (1010 to 1149°C). Other nickel alloys may exhibit carbide precipitation and should not be worked in the sensitization range. Postbending heat treatment may be required. For more information contact nickel product manufacturers such as Huntington Alloys.[22]

Titanium can be bent using draw bending equipment. However, those parts of the equipment which will wipe against the inner and outer surfaces of the pipe should be of aluminum bronze to minimize galling. For better formability, the pipe, the pressure die, and the mandrel should be heated to a temperature between 350 and 400°F (177 and 204°C). Unalloyed titanium can be hot worked in the temperature range of 1000 to 1400°F (538 to 760°C). Titanium alloy grade 12 requires a temperature range of 1400 to 1450°F (760 to 788°C). Heat treatment of titanium is recommended after forming. This is usually a furnace treatment at 1000 to 1100°F (538 to 593°C) for a minimum of ½ h for the unalloyed grades and 1 h for the alloy

TABLE A6.2 Temperature Range for Hot Bending of Nickel and Nickel Alloy Pipe and Tube

Material	Spec. no.	Alloy	Temperature range (°F)
Nickel	SB-161	N02200	1200–2300
Low carbon nickel	SB-161	N02201	1200–2300
Nickel-copper	SB-165	N04400	1700–2150
Ni-Cr-Fe	SB-167, SB-517	N06600, N06690	1850–2300
Ni-Fe-Cr	SB-407, SB-514	N08800, N08810	1850–2200

Source: Adapted from ASME Boiler & Pressure Vessel Code, 1995 ed., Section VIII Div. 1 Table NF-4.

(grade 12). Prolonged exposure to temperatures in excess of 1100°F (593°C) will result in heavy scaling and require some type of descaling treatment.

Other Forming Operations. Some additional forming operations which can be performed in a pipe shop are extrusion, swaging, and lapping. Extrusions involve forming outlets in pipe by pulling or pushing a hemispherical or conical die from the inside of the pipe through an opening in the wall. The work may be done hot or cold depending on the characteristics of the material. Ferritic steels, austenitic steels, and nickel alloys are usually formed hot; aluminum and copper are usually formed cold. In order to assure that the outlet will have sufficient reinforcement, it is necessary to increase the wall thickness of the header as a function of the outlet size desired. An increase of 30 percent may be needed for large outlet-to-header ratios.

Swaging involves the size reduction of pipe ends by forging, pressing, or rolling operations. The operation is usually used to produce reductions of one to two pipe sizes. Ferritic steels, austenitic steels, and nickel alloys are usually formed hot. Aluminum and copper are formed cold.

In lapped joints, a loose flange is slipped over the end of the pipe which is then heated to forging temperature, upset, and flared at right angles to the pipe axis. After heat treatment and cooling, the lapped section is machined on the face to attain a good gasket surface and on the back for good contact with the flange. The finished thickness of the lapped flange should be equal to or exceed the thickness of the pipe.

Layout, Assembly, and Preparation for Welding. In fabrication shops, piping subassemblies are often assembled on layout tables. A projection of the subassembly is laid out on the table in chalk. This establishes the baseline for locating the components and terminal dimensions of the subassembly, and the components are assembled relative to the layout. Prior to fit-up, it is essential that all weld surfaces be properly cleaned of rust, scale, grease, paint, and other foreign substances which might contaminate the weld. If moisture is present, the weld joint should be preheated. For alloy steels the heat-affected zone (HAZ) which results from thermal cutting should be removed by grinding or machining.

Depending on the configuration of the subassembly and root opening required by the welding procedure, some allowance may be required for weld shrinkage in the longitudinal direction. Actual shrinkage is difficult to predict and can vary considerably because of the many variables involved. For most open butt and backing ring joints, one-half the root opening is a reasonable allowance. For joints with other root configurations it may be as little as 1⁄16 in (2.0 mm) for the lighter walls, increasing to as much as 5⁄32 in (8 mm) for walls 4 to 5 in (100 to 127 mm) thick.

Each weld joint should be carefully aligned within required tolerances using alignment fixtures, spacers, or jigs if necessary. Poor alignment may result in a poor weld. Once alignment is attained, the joint is usually tack-welded to maintain the alignment. The process used for tacking is usually that being used for the root-pass weld. Numbers and size of tacks should be kept to a minimum, but if the subassembly is to be moved elsewhere for weld out, their size must be sufficiently large so as not to crack during the moving operation. Temporary lugs or spacer bars may also be used for this purpose provided they are of a compatible material, the temporary welds are removed, and the surface examined after removal to assure sound metal. Tack welds made by the shielded metal are welding (SMAW) or gas metal arc welding (GMAW) processes at the root of a weld should be removed or ground smooth since they can become a source of lack of fusion. For gas tungsten arc (GTAW) root welds, tacks usually fuse the adjacent lands to each other or to the insert, and filler metal is often not used. Tack welds are then fused into the weld during the root pass without further preparation. After tacking, the recommended practice is to complete the root pass and one or more weld out passes before starting to complete the weld by other processes to avoid burning through the relatively thin root.

Welding. Welding constitutes the bulk of the work involved in fabrication of modern piping systems, so it is essential for all involved to have a good working knowledge of this subject.

Procedure and Personnel Qualifications. All of the ASME Boiler and Pressure Codes and most of the ASME B31 Pressure Piping Codes reference ASME Section IX for the requirements for qualifying welding procedures and welding personnel. The ASME B31.4,[23] B31.8,[24] and B31.11[25] Codes also permit qualification to API-1104,[26] published by the American Petroleum Institute. ASME B31.5[27] permits qualification to AWS D10.9.[28]

The purpose of procedure qualification is to assure that the particular combination of welding process, base metal, filler material, shielding fluxes or gases, electrical characteristics, and subsequent heat treatment is capable of producing a joint with the required chemical and physical characteristics.

The purpose of personnel qualification is to assure that the welder or welding machine operator is capable of performing the operation in accordance with a qualified procedure in the required position.

Procedure Qualification. ASME Section IX requires the preparation of a Welding Procedure Specification (WPS), which lists the various parameters to be used during welding. When each WPS is qualified, the parameters used in the qualification are recorded in a Procedure Qualification Record (PQR).

For each type of welding process, ASME Section IX has established a series of variables. These are base metal, filler metal, position, preheat, postweld heat treatment, shielding gases, joint configuration, electrical characteristics, and technique. Base metal must not only be considered from a chemical and physical properties point of view, but in piping, the diameter and thickness of the test coupon limits the qualification to certain sizes. Differing fluxes, use of solid or gaseous backing, and single- or multipass techniques are some of the other variables which must be considered. Careful study of Section IX, AWS D10.9, or of API 1104 as may be applicable is in order.

The variables for welding are classed as essential, supplementary essential, and nonessential. The manner in which the variables are classed can vary depending on the welding process. That is, what may be classed as an essential variable for one may be a nonessential variable for one another. For a given process, each combination of essential variables must be qualified separately. A change in any one of them requires a new qualification.

When welds must meet certain fracture toughness requirements, the supplementary essential variables become essential and the procedure must be requalified for the particular combination of essential and supplementary essential variables.

Nonessential variables do not require requalification but should be referenced in the WPS.

Personnel Qualification. The fabricator and/or installer must qualify each welder or welding operator for the welding processes to be used during production welding. The performance qualification must be in accordance with a qualified WPS. Each performance qualification is also governed by a series of essential variables which are a function of the welding process for which the welder is being qualified.

The welder or welding operator may be qualified by mechanical tests or in some cases by radiographic examination of the test coupon. The record of each performance qualification is kept on a Welder/Welding Operator Performance Qualification (WPQ). Under ASME Section IX rules, a qualified welder who has not welded in a specific process within a specified period of time must be requalified for that process. API 1104 and AWS D10.9 have similar requalification provisions.

Welding Processes. Currently the most commonly used welding processes for fabrication of piping are SMAW, submerged arc welding (SAW), GTAW, GMAW, and flux core arc welding (FCAW). Some special applications may involve plasma arc welding (PAW) or electron beam welding (EBW), but their application to piping is still rare. However, any welding process which can be qualified under the requirements of ASME Section IX is acceptable. Detailed descriptions of these various processes and their variations may be found in the *Welding Handbook*.[16] This section will limit discussion to their application to piping.

For shop work, the best efficiency in all welding processes is attained when the pipe axis is horizontal and the piece is rotated so that welding is always done in the flat position. This is referred to as the 1G position. Other positions are 2G (pipe vertical and fixed, weld horizontal); 5G (pipe horizontal and fixed, weld a combination of flat, vertical, and overhead); and 6G (pipe inclined at 45° and fixed). See ASME Section IX.

Shielded Metal Arc Welding. SMAW has been the mainstay for pipe welding for many years, but it is rapidly being displaced by newer, more efficient processes. It is a process where an arc is manually struck between the work and a flux-coated electrode which is consumed in the weld. The core wire serves as the filler material, and the flux coating disintegrates to provide shielding gases for the molten metal, scavengers, and deoxidizers for the weld puddle and a slag blanket to protect the molten metal until it is sufficiently cool to prevent oxidation. It can be used in all positions, for upward or downward progression, and for root pass welding depending on the flux composition. Each weld pass is about ⅛ in thick, and before subsequent passes are made the slag must be removed and the surface prepared by removing irregularities which could entrap slag during subsequent passes.

Submerged Arc Welding. Unlike SMAW, SAW is an automatic or semiautomatic process. For circumferential welds in pipe the welding head is fixed for flat welding and the work is rotated under the head (1G position). It is used most efficiently in groove butt welds in heavy wall materials with pipe sizes NPS 6 (DN 150) and larger. The arc is created between the work and a bare solid wire or composite electrode which is consumed during the operation. The electrode comes in coils. Shielding is accomplished by a blanket of granular, fusible material called a *flux* which covers the arc and molten metal by forming a slag blanket to prevent oxidation of the molten metal until it has sufficiently cooled. Particular wire-flux combinations are required to assure that the deposited weld has the needed chemical and physical properties. This process has the greatest deposition rate and accordingly is the preferred process wherever possible. Because of the high heat input, care must be taken to assure that the interpass temperature is controlled to minimize sensitization in austenitic stainless steels or loss of notch toughness in ferritic steels. High heat input can also result in excessive penetration, so this process cannot be used effectively for root pass welding unless the root is deposited against a backing ring or sufficient backing is provided by two or more weld passes made by the shielded metal arc or a gas-shielded arc process.

Gas Shielded Arc Welding. The term *gas-shielded arc welding* applies to those welding processes where the arc and molten metal are shielded from oxidation by some type of inert gas rather than by a flux.

1. *Gas tungsten arc welding:* GTAW is a form of gas-shielded arc welding where the arc is generated between the work and a tungsten electrode which is not consumed. The filler metal must be added from an external source, usually as bare filler rod or preplaced consumable insert. The filler metal is melted by the heat of the arc, and shielding gases are usually argon or helium. Alloying elements are always in the filler material. GTAW is considered to be the most desirable process for making root welds of highest quality. Techniques using added filler metal or preplaced filler metal as inserts are equally effective in manual and automatic applications.

Automatic versions can be used in all positions provided sufficient clearance is available for the equipment. Automatic versions also require tighter fit-up requirements since the equipment is set to specific parameters and will not recognize variations outside of these limits, such as a welder would do in manual applications.

In automatic GTAW, the welding head orbits the weld joint on a guide track placed on the pipe adjacent to the joint to be welded. The welding head contains motors and drive wheels needed to move the head around the track, a torch to create the arc, and a spool of filler wire. Welding current, voltage, travel speed, wire feed rate, and oscillation are controlled from an external source. These parameters may be varied by the operator as the welding head traverses the weld. Oscillation and arc energy can be adjusted to permit greater dwell time and heat input into the side walls. Automatic GTAW welds are usually deposited as a series of stringer beads to minimize the effects of high interpass temperature.

2. *Gas metal arc welding:* GMAW is a type of gas-shielded welding generally used in the manual mode but adaptable to automation. The filler wire is the electrode and is furnished in coils or spools of solid wire. Is is fed automatically into the joint, melted in the arc, and deposited in the weld groove. Alloying elements arc in the wire, and shielding gas may be argon, helium, nitrogen, carbon dioxide, or combinations thereof, depending on the application.

Depending on the equipment and the heat input settings, filler metal can be transferred across the arc is several modes. In *short-circuiting transfer*, the electrode actually touches the work where it short-circuits, melts, and restarts the arc. This process has low heat input and accordingly low penetrating power. It can often result in lack of fusion. Because of the low heat input, however, it can be effectively used for open-butt root pass welding.

In *spray transfer*, the heat input parameters are sufficiently high to transfer the molten electrode across the arc as small droplets. Argon or argon-rich gases are used for shielding, resulting in a very stable spatterfree arc. Because of the high arc energy, it is normally used in the flat (1G) position. For all-position welding, a procedure which superimposes high amplitude pulses of current on a low-level steady-state current at regular intervals is often used. This results in a discrete transfer of metal with lower heat input needed for all-position welding.

3. *Flux core arc welding:* FCAW is a variation of GMAW where a composite electrode is substituted for the solid wire. The electrode is a tubular wire containing a flux material. Depending on the application, the arc may be self-shielding, or shielding gases may be used. Because of its high deposition rate this process is rapidly being developed for shop and field welding of piping.

Base Metal. Base metal is one of the essential variables for welding qualification. Because there are so many base metals to be welded, ASME Section IX has established a system of P Numbers and Group Numbers. Each base metal is assigned to a specific P Number depending on characteristics such as composition, weldability, and mechanical properties. Each P Number is further subdivided into Group Numbers depending on fracture toughness properties. See Table A6.3. When a procedure is qualified with a base metal within a particular P Number, it is also qualified for all other base metals within that P Number. When fracture toughness is a requirement, qualification is limited to base metals within the same P Number *and* Group Number. For example: A 106 Gr. B pipe is P No. 1 Gr. No. 1, while an A 105 flange is P No. 1 Gr. No. 2. Since both are P No. 1, qualification on either qualifies both when fracture toughness is not a factor. However, should fracture toughness become a requirement, a separate qualification would be required for each to itself and to each other.

Filler Metals. Electrodes, bare wire, wire-flux combinations, and consumable inserts which form a part of the finished weld are classed as filler materials. Most are covered by AWS and ASME specifications. See ASME Section II Part C.[29]

When the filler material is part of the electric circuit, it is designated as an

TABLE A6.3 ASME P Numbers and Group Numbers for Some Typical Piping Materials

Nominal composition	P No.	Group No.
Carbon Steel—65 ksi & under	1	1
—65 ksi to 75 ksi	1	2
C-½Mo & ½Cr-½ Mo—65 ksi & under	3	1
—70 ksi to 75 ksi	3	2
1Cr-½Mo & 1¼Cr-½ Mo-Si	4	1
2¼Cr-1Mo	5A	1
5Cr-½Mo, & 9Cr-1Mo	5B	1
9Cr-1Mo-V	5B	2
Type 304 & 316 Stainless	8	1
Type 309 & 310 Stainless	8	2
3½ Ni Steel	9B	1
Al & Al alloys	21 thru 25	—
Cu & Cu alloys	31 thru 35	—
Ni & Ni alloys	41 thru 47	—

Source: Selected from ASME Boiler & Pressure Vessel Code Section IX, 1995 ed.

electrode. If it is fed externally and melted by the heat of the arc, it is designated as a rod. Coated electrodes for SMAW come in straight lengths. Bare rods for GTAW come in straight lengths or spools. Electrode wire for GMAW and SAW are in spools or coils, while composite electrodes for FCAW are in spools.

Each specification incorporates a system of identification so that the filler materials manufactured by different suppliers which have equivalent characteristics are identified by the same number.

For qualification purposes, they are classified in ASME Section IX with F Numbers and A Numbers. Changes in filler metal from one F Number or A Number to another require requalification.

One of the problems associated with coated electrodes for SMAW is the introduction of hydrogen into the arc atmosphere and finished weld, resulting in hydrogen-induced cracking. To minimize this problem, low-hydrogen-type coatings are used, but these can absorb moisture from the atmosphere. Once a sealed can of electrodes is opened, the electrodes should be stored in an oven at about 250 to 350°F (120 to 175°C) or other temperature recommended by the manufacturer. Once removed from the oven, low-hydrogen electrodes should be maintained at 175°F (80°C) minimum until consumed. Baking to remove moisture is recommended for electrodes which have been out of the oven for several hours. Refer to the manufacturers' recommendations.

A problem associated with welding of fully austenitic stainless steel is microfissuring. To combat this problem the chemical composition of the filler material is adjusted to produce a weld deposit with small amounts of ferrite. ASME III requires that filler materials used in welding austenitic stainless steels contain a minimum of 5 percent ferrite. Ferrite, however, can be a problem at cryogenic and high temperatures. For cryogenic services the weld metal may not possess the fracture toughness capabilities of the base metal, and the ferrite content should be kept as low as possible. Alternatively, fully austenitic fillers may be required, but these are more crack-sensitive. For very high temperatures ferrite in the weld may convert to a brittle phase called *sigma.* For this reason applications over about 800°F (427°C) usually require a minimum of 3 percent ferrite for weldability but not exceeding 7 percent to minimize sigma formation.

Preheat and Interpass Temperature. Ferritic materials undergo metallurgical phase changes when cooling from welding to ambient temperature. Mild steels which contain no more than 0.20 percent carbon and 1 percent manganese can be welded without preheat when the thickness is 1 in (25 mm) or less. However, as the chemical composition changes by increases of carbon, manganese, and silicon or the addition of chromium and certain other alloying elements, preheating becomes increasingly important since the higher carbon and chrome molybdenum steels can develop more crack-sensitive martensitic, matensitic-bainitic, and other mixed phase structures when cooled rapidly from welding temperatures.

There is also a potential for hydrogen from SMAW electrode coatings or from moisture on the base metal surface to be dissolved in the weld. Also as the weld cools, stresses caused by shrinkage are imposed on the parts and distortion can result; and as thickness increases, thermal shock from the heat of welding can induce cracking more readily.

Preheating prior to welding is a solution to most of these problems. Preheating slows the cooling rate of the weld joint and results in a more ductile metallurigical structure in the weld metal and HAZ. It permits dissolved hydrogen to diffuse more readily and helps to reduce shrinkage, distortion, and possible cracking caused by the resultant residual stresses. It raises the temperature of the material sufficiently high to be above the brittle fracture transition zone for most materials.

The codes vary regarding preheat requirements. Some have mandatory require-

TABLE A6.4 Typical Preheat Requirements

P No.	Temp. (°F)	Composition/thickness limits
1	175	For *both* a max. specified carbon content >0.30% *and* thickness >1 inch.
	50	For all others.
3	175	For *either* a min. specified tensile strength >60 ksi, *or* thickness >½ in.
	50	For all others.
4	250	For *either* a min. specified tensile strength >60 ksi, *or* thickness >½ in.
	50	For all others.
5A and 5B	400	For *either* a min. specified tensile strength >60 ksi, *or both* a min. specified Cr content >6.0% *and* thickness >½ in.
	300	For all others.
6	400	For all materials.
7	50	For all materials.
8	50	For all materials.
9A	250	For all materials.
9B	300	For all materials.
10I	300	With a max. interpass temperature of 450°F.

Source: ASME B31.1 1995 ed.

ments while others give suggested levels. For example, for carbon steel welding, the B31.1 Code *requires* preheating to a temperature of 175°F (80°C) when the carbon content exceeds 0.30 percent *and* the thickness of the joint exceeds 1 in. B31.3 *recommends* preheating to 175°F (80°C) when the base metal specified strength exceeds 71 ksi *or* the wall thickness is equal to or greater than 1 in (25 mm). ASME III Section *suggests* a preheat of 200°F (95°C) when the maximum carbon content is 0.30 percent or less *and* the wall thickness exceeds 1½ in for P No. 1 Gr. No. 1, or 1 in (25 mm) for P No. 1 Gr. No. 2. It also suggests a 250°F (120°C) preheat for materials with carbon in excess of 0.30 percent and wall thicknesses exceeding 1 in (25 mm). The ASME B31.4 and B31.8 Codes require preheat based on carbon equivalents. When the carbon content (by ladle analysis) exceeds 0.32 percent, or the carbon equivalent (C + ¼ Mn) exceeds 0.65 percent, preheating is required. The reader is advised to consult the specific codes for preheating requirements. See Table A6.4 for some typical preheat requirements.

It should be noted that for the 9Cr-1Mo-V (P No. 5B Gr. 2) material some manufacturers suggest a preheat of 350°F (177°C) for GTAW and 400 to 450°F (204 to 232°C) for other types of welding regardless of thickness.

While it is preferred that preheat be maintained during welding and into the postweld heat treatment cycle without cooling, this may not always be practical. The B31.1 Code permits slow cooling of the weld to room temperature provided the completed weld deposit is a minimum of ⅜ in (9.5 mm) or 25 percent of the final thickness, whichever is less. For P No. 5B and P No. 6 materials some type of intermediate stress relief is required.

For the 9Cr-1Mo-V material it is recommended that the finished weld be heated to 500°F (260°C), held at that temperature for 2 hours, and allowed to cool slowly in still air by wrapping it with insulating material.

Too much heat during welding can also be a problem. Where notch toughness is a requirement, prolonged exposure to temperatures exceeding 600°F (316°C) can temper the base metal. Controlling the interpass temperature is required to minimize this problem. Interpass temperature control means allowing the temperature of the joint to cool below some specified level before the next pass is deposited.

Because of its martensitic structure, a maximum interpass temperature of 600°F (316°C) should be observed when welding 9Cr-1Mo-V material.

In welding of austenitic stainless steels, sensitization of the base metal HAZ will result from the heat and welding. Here the solution is to weld with as low a heat input as possible at the highest possible speed to minimize the precipitation of carbides (sensitization). A maximum interpass temperature of 300 to 350°F (149 to 177°C) is usually employed.

Weld Joint Design

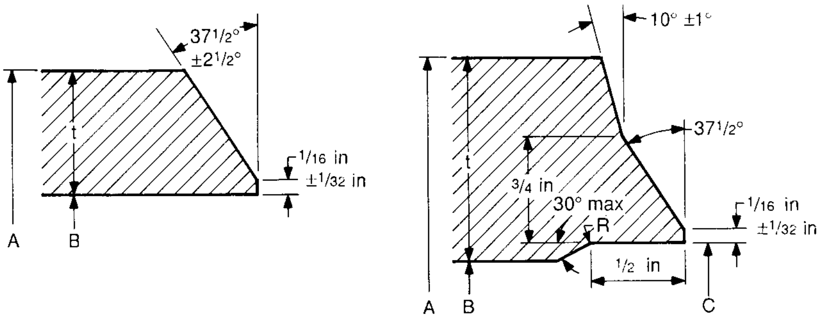
Butt Welds. A butt joint is defined as one in which the members being joined are in the same plane. The circumferential butt joint is the most universally used method of joining pipe to itself, fittings, flanges, valves, and other equipment. The type of end preparation may vary depending on the particular preferences of the individual, but in general the bevel shape is governed by a compromise between a root sufficiently wide to assure a full-penetration weld but not so wide as to require a great deal of filler metal.

In the shop, the inside surface of large-diameter pipe joints is often accessible. In this case the joint is most often double-welded (welded from both sides), and a double V bevel is used. For heavier walls, machined double U bevels can be used. However, the vast majority of piping butt welds must be made from one side only. For this situation the most frequently specified shapes are the V bevel, compound bevel, and U bevel, all of which can have varying angles, lands, and tolerances. See Fig. A6.15. Recent advances in SAW narrow-gap welding as applied to piping butt welds have cut the volume of filler metal significantly in pipe walls that are 2 in (51 mm) and thicker. The 30 or 37½° (60 or 75° included angle) V bevel is most often performed integrally with the cutting operation by machine, oxyfuel gas, or arc cutting. Other bevel shapes such as the compound V, U, J bevels, or combinations thereof require machining in lathes or boring mills.

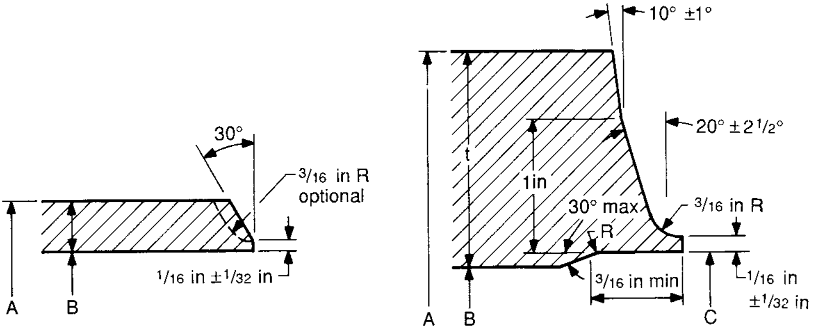
1. *Alignment:* Alignment for butt welding can often be a frustrating task since it is influenced by the material; pipe diameter, wall thickness, out-of-roundness tolerances; welding process needs; and design requirements.

When a joint can be double welded, the effects of misalignment are minimized since both inner and outer weld surfaces can be blended into the base metal, and any remaining offsets can be faired out. ASME Section III gives a table of allowable offsets due to misalignment in double-welded joints. See Table A6.5. All resulting offsets must be faired to a 3:1 taper over the finished weld.

For single-welded joints alignment can be more difficult, since the inside surface is not accessible. The degree of misalignment is influenced by many factors and depending on the type of service application may or may not be significant. The various codes impose limits on inside-diameter misalignment. This is to assure that the stress intensification resulting from the misalignment is kept within a reasonable value. The B31.1 Code requires that the misalignment between ends to be joined not exceed 1⁄16 in (2.0 mm), unless the design specifically permits greater amounts. See Fig. A6.16. The B31.4 and B31.8 Codes do not require special treatment unless the difference in the nominal walls of the adjoining ends exceeds 3⁄32 in (2.5 mm).



(*a*) Walls ≤ 1 in (*b*) Walls > 1 in



(*c*) GTA root – walls > 1/8 to 3/8 in (*d*) GTA root – walls > 3/8 in

FIGURE A6.15 Typical weld end bevels. (*a*) Walls ≤ 1 in; (*b*) walls > 1 in; (*c*) GTA root walls > ⅛ to ⅜ in; (*d*) GTA root walls > ⅜ in.

ASME Section III on the other hand requires that the inside *diameters* of the adjoining sections match within 1/16 in (2.0 mm) to assure good alignment. Counterboring is usually required to attain this degree of alignment.

The welding process and NDEs to be employed also bear on misalignment limits. Some welding processes can tolerate fairly large misalignments while others, notably

TABLE A6.5 Maximum Allowable Offset in Joints Welded from Both Sides

	Direction of joints	
Section thickness (in)	Longitudinal	Circumferential
Up to ½, incl.	¼*t*	¼*t*
Over ½ to ¾, incl.	⅛ in	¼*t*
Over ¾ to 1½, incl.	⅛	3/16 in
Over 1½ to 2, incl.	⅛ in	⅛*t*
Over 2	Lesser of 1/16*t* or ⅜ in	Lesser of ⅛*t* or ¾ in

Source: ASME Boiler & Pressure Vessel Code Section III 1995 ed.

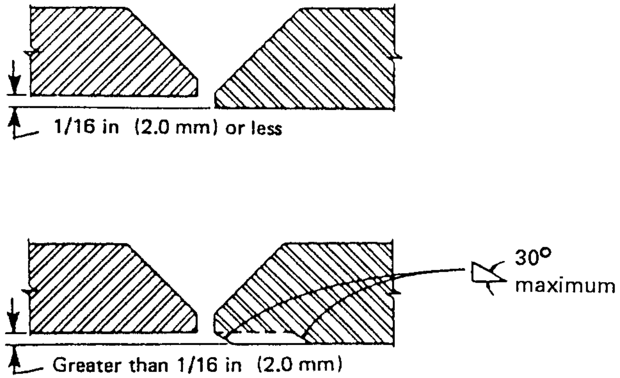


FIGURE A6.16 Butt welding of piping components with internal misalignment. (*ASME B31.1 Power Piping Code, 1995 ed.*)

gas tungsten arc root pass welding with and without consumable inserts require closer tolerances. See PFI ES-21.[30] Radiographic or ultrasonic examinations of misaligned areas may show unacceptable indications if the degree of misalignment is too great.

A review of the tolerances permitted in the manufacture of various types of pipe, fittings, and forgings immediately reveals that in many situations the probable inside diameter and wall thickness variations will produce unacceptable misalignment situations. Out-of-roundness in lighter wall materials can add to the problem.

When most of the pipe comes from the same rolling and the fittings from the same manufacturing lot, variations in tolerances are minimal and the pipe and fittings can be assembled for most common applications without a great deal of adjustment. Out-of-round problems in lighter walls are handled with internal or external round-up devices.

To assure that all components will be capable of alignment in the field, it is common practice for the designer to specify that the inside diameters of all matching components be machine counterbored to some specified dimension. This practice is also desirable for shop welding of heavier wall piping subassemblies. PFI ES-21 contains a set of uniform dimensions for counterboring of seamless hot-rolled pipe ordered to A106 or A335 by NPS and schedule number. See Table A6.6.

The C dimension is determined from the following equation:

$$C = A - \tfrac{1}{32}\text{ in} - 2 \times t_m - 0.010\text{ in}$$

where A = pipe outside diameter
$\tfrac{1}{32}$ in = pipe outside diameter under tolerance
t_m = mill minimum wall = $0.875t$
t = mill nominal wall
0.010 = a boring tolerance

This simplifies to:

$$C = A - 0.041 - 1.75t \text{ in} \qquad \text{(A6.2)}$$
$$C = A - 1.04 - 1.75t \text{ mm} \qquad \text{(A6.2M)}$$

The tolerance on C is $+0.010 - 0.040$ in ($+0.25$ mm, -1.02 mm).

TABLE A6.6 Internal Machining for Circumferential Butt Welds

Nominal pipe size	Schedule number or wall	Nominal O.D. *A* (in)	Nominal I.D. *B* (in)	Nominal wall thickness *t* (in)	Machined I.D. of pipe *C* tolerance +0.010, −0.040 (in)
3	XXS	3.500	2.300	0.600	2.409
4	XXS	4.500	3.152	0.674	3.279
5	160	4.500	4.313	0.625	4.428
	XXS	5.563	4.063	0.750	4.209
6	120	6.625	5.501	0.562	5.600
	160	6.625	5.187	0.719	5.327
	XXS	6.625	4.897	0.864	5.072
8	100	8.625	7.437	0.594	7.546
	120	8.625	7.187	0.719	7.327
	140	8.625	7.001	0.812	7.163
	XXS	8.625	6.875	0.875	7.053
	160	8.625	6.813	0.906	6.998
10	80	10.750	9.562	0.594	9.671
	100	10.750	9.312	0.719	9.452
	120	10.750	9.062	0.844	9.234
	140	10.750	8.750	1.000	8.959
	160	10.750	8.500	1.125	8.740
12	60	12.750	11.626	0.562	11.725
	80	12.750	11.374	0.688	11.507
	100	12.750	11.062	0.844	11.234
	120	12.750	10.750	1.000	10.959
	140	12.750	10.500	1.125	10.740
	160	12.750	10.126	1.312	10.413
14 O.D.	60	14.000	12.812	0.594	12.921
	80	14.000	12.500	0.750	12.646
	100	14.000	12.124	0.938	12.319
	120	14.000	11.812	1.094	12.046
	140	14.000	11.500	1.250	11.771
	160	14.000	11.188	1.406	11.498
16 O.D.	60	16.000	14.688	0.656	14.811
	80	16.000	14.312	0.844	14.484
	100	16.000	13.938	1.031	14.155
	120	16.000	13.562	1.219	13.827
	140	16.000	13.124	1.438	13.442
	160	16.000	12.812	1.594	13.171
18 O.D.	40	18.000	16.876	0.562	16.975
	60	18.000	16.500	0.750	16.646
	80	18.000	16.124	0.938	16.319
	100	18.000	15.688	1.156	15.936
	120	18.000	15.250	1.375	15.553
	140	18.000	14.876	1.562	15.225
	160	18.000	14.438	1.781	14.842

TABLE A6.6 Internal Machining for Circumferential Butt Welds (*Continued*)

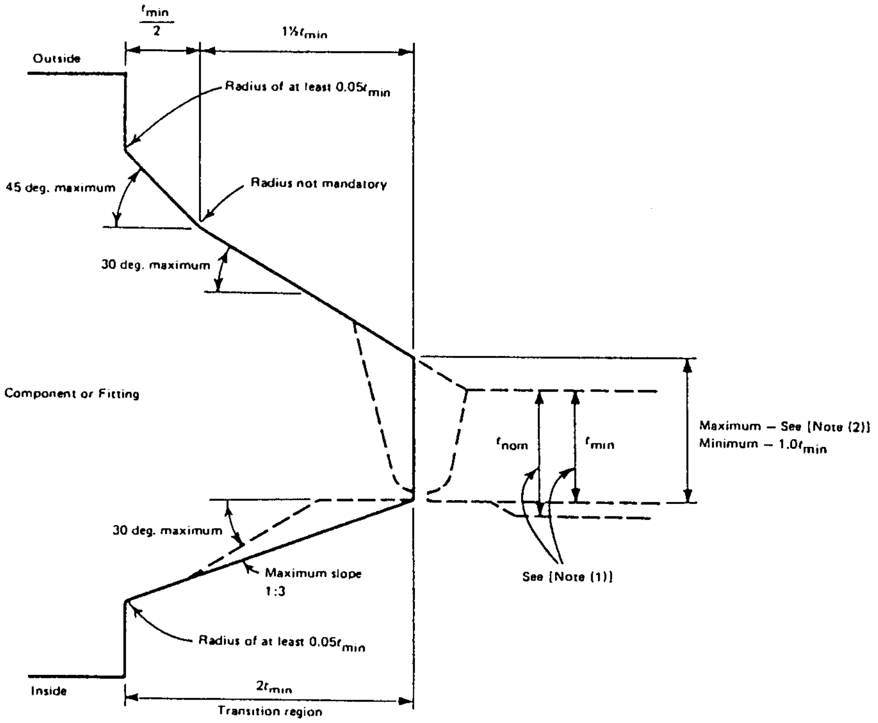
Nominal pipe size	Schedule number or wall	Nominal O.D. *A* (in)	Nominal I.D. *B* (in)	Nominal wall thickness *t* (in)	Machined I.D. of pipe *C* tolerance +0.010, −0.040 (in)
20 O.D.	40	20.000	18.812	0.594	18.921
	60	20.000	18.376	0.812	18.538
	80	20.000	17.938	1.031	18.155
	100	20.000	17.438	1.281	17.717
	120	20.000	17.000	1.500	17.334
	140	20.000	16.500	1.750	16.896
	160	20.000	16.062	1.969	16.515
22 O.D.	—	22.000	20.750	0.625	20.865
	60	22.000	20.250	0.875	20.428
	80	22.000	19.750	1.125	19.990
	100	22.000	19.250	1.375	19.553
	120	22.000	18.750	1.625	19.115
	140	22.000	18.250	1.875	18.678
	160	22.000	17.750	2.125	18.240
24 O.D.	30	24.000	22.876	0.562	22.975
	40	24.000	22.624	0.688	22.757
	60	24.000	22.062	0.969	22.265
	80	24.000	21.562	1.219	21.827
	100	24.000	20.938	1.531	21.280
	120	24.000	20.376	1.812	20.788
	140	24.000	19.876	2.062	20.350
	160	24.000	19.312	2.344	19.859

Source: Pipe Fabrication Institute PFI ES-21.

For other types of seamless pipe, longitudinally welded pipe, forged and bored pipe, and other specialties, the tolerances on the outside diameter and wall thickness are different. The machining tolerance required for some welding processes may also be different. However, similar logic may be applied in determining *C* dimensions for these products. (See PFI ES-21.)

It should be noted from Table A6.6 that the tabulation applies to wall thickness greater than ½ in (12.7 mm). While one can calculate a *C* dimension for lighter walls, the combination of outside diameter tolerance and wall thickness tolerance will usually result in a calculated *C* which is often smaller than the actual bore of the pipe. The difference is most often relatively small, and the existing diameter will usually be suitable for alignment of most welds. In those cases where it is considered essential, the outside diameter at the end can be sized to provide stock for machining, but care is required to assure that the minimum wall is maintained. Where counterboring is used, the machined surface should taper into the existing inside surface at an angle of 30° maximum. See Fig. A6.17.

There are many instances where round-up devices and counterboring are insufficient remedies for misalignment. On occasion it may be necessary to expand the ends where counterboring would violate minimum wall requirements. Most of the codes permit the use of weld metal deposits (weld buildup) both on the inside and outside surfaces of the weld end in order to attain the required alignment. In



GENERAL NOTES:

(a) Weld bevel is shown for illustration only

(b) The weld reinforcement permitted by NC-4426 may lie outside the maximum envelope.

NOTES:

(1) The value of t_{min} is whichever of the following is applicable:
  (a) the minimum ordered wall thickness of the pipe;
  (b) 0.875 times the nominal wall thickness of pipe ordered to a pipe schedule wall thickness which has an under tolerance of 12.5%;
  (c) the minimum ordered wall thickness of the cylindrical welding end of a component or fitting (or the thinner of the two) when the joint is between two components.

(2) The maximum thickness at the end of the component is:
  (a) the greater of t_{min} + 0.15 in. or $1.15t_{min}$ when ordered on a minimum wall basis;
  (b) the greater of t_{min} + 0.15 in. or $1.0t_{nom}$ when ordered on a nominal wall basis.

FIGURE A6.17 Welding end transitions—maximum envelope. (*ASME Boiler and Pressure Vessel Code, Sec. III, 1995 ed.*)

using this alternative, consideration must be given to other factors such as radial shrinkage, imperfections in the weld buildup which may show on NDE, need for pre- and postweld heat treatment, and possible sensitization of austenitic stainless steels.

2. *Unequal wall thickness:* In most piping systems there are components such as valves, castings, heavier header sections, and equipment nozzles which are welded to the pipe. In such instances the heavier sections are machined to match the lighter pipe wall and the excess thickness tapered both internally and externally to form a transition zone. Limits imposed by the various codes for this transition zone are fairly uniform. The external surface of the heavier component is tapered at an angle of 30° maximum for a minimum length equal to 1½ times the pipe minimum wall thickness and then at 45° for a minimum of ½ times the pipe minimum wall. Internally, either a straight bore followed by a 30° slope or a taper bore at a maximum slope of 1 to 3 for a minimum distance of 2 times the pipe minimum wall are required. See Fig. A6.17. The surface of the weld can also be tapered to accommodate differing thickness. This taper should not exceed 30°, although some codes limit the taper to 1 to 4. It may be necessary to deposit weld metal to assure that these limits are not violated.

Fillet Welds. Circumferential fillet welds are used in piping systems to join slip-on flanges and socket welding fittings and flanges to pipe. In welding slip-on flanges to pipe, the pipe is inserted into the flange and welded with two fillet welds, one between the outside surface of the pipe and the hub of the flange and the other between the inside surface of the flange and the thickness of the pipe. See Fig. A6.18. Alignment is relatively simple since the pipe fits inside the flange. The B31.1 Code requires that the fillet between the hub and the pipe have a minimum weld leg of 1.09 times the pipe nominal wall or the thickness of the hub, whichever is smaller. The weld leg of the front weld must be equal to the pipe nominal wall or ¼ in, whichever is smaller. The gap between the outside diameter of the pipe and flange inside diameter may increase with size, so the size of the fillet leg should be adjusted to compensate for this situation.

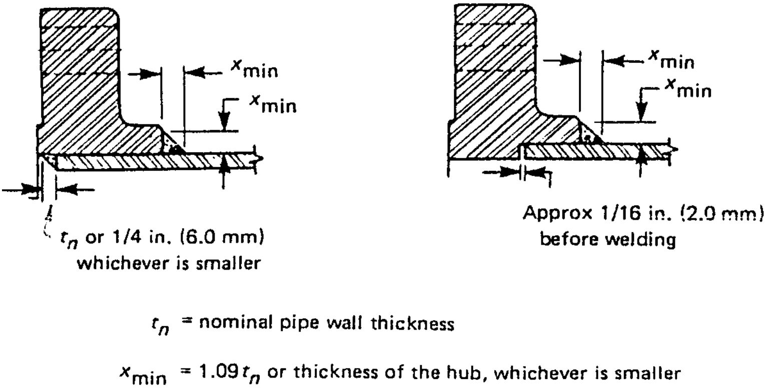


FIGURE A6.18 Slip-on and socket welding flange welds. (*ASME B31.1, 1995 ed.*)

Fillet welds are also used for circumferential welding of pipe to socket fittings. Socket weld fittings and flanges are available in sizes up to NPS 4 (DN 100) but are most frequently used in sizes NPS 2 (DN 50) and smaller. Alignment is not a problem since the pipe fits into the fitting socket. Some codes require that the fillet have uniform leg sizes equal to 1.09 times the pipe nominal wall or be equal to the socket wall, whichever is smaller. In making up socket joints it is recommended that the pipe not be bottomed in the socket before welding. B31.1 and ASME Section III suggest a 1⁄16-in (2.0 mm) gap. In high-temperature service especially, the pipe inside the socket will expand to a greater degree than the socket itself, and the differential expansion may result in unwanted shear stress in the fillet and possible cracking during operation.

Intersection-Type Weld Joints. Intersection-type weld joints occur when the longitudinal axes of the two components meet at some angle. Such is the case where nozzle, lateral, and wye intersections are fabricated by welding. Weld joints in these cases may be butt, fillet, or a combination thereof. Nozzles are made either by *set-on* or *set-through* construction. In set-on construction, the opening in the header pipe is made equal to the inside diameter of the branch pipe. The branch pipe is contoured to the outside diameter of the header and beveled so that the weld is made between the outside surface of the header and through the thickness of the branch. The through thickness weld is covered by a fillet weld to blend it into the header pipe surface. In set-through construction an opening is cut in the header pipe equal to the outside diameter of the branch pipe and beveled. The branch pipe is contoured to match the inside diameter of the header. See Fig. A6.19. The weld is between the outside surface of the branch and through the thickness of the header and is covered with a fillet weld to blend it into the outside surface of the branch. Either type of construction is acceptable; the usual practice is to use set-on since the volume of required weld metal is less. However, when the header is

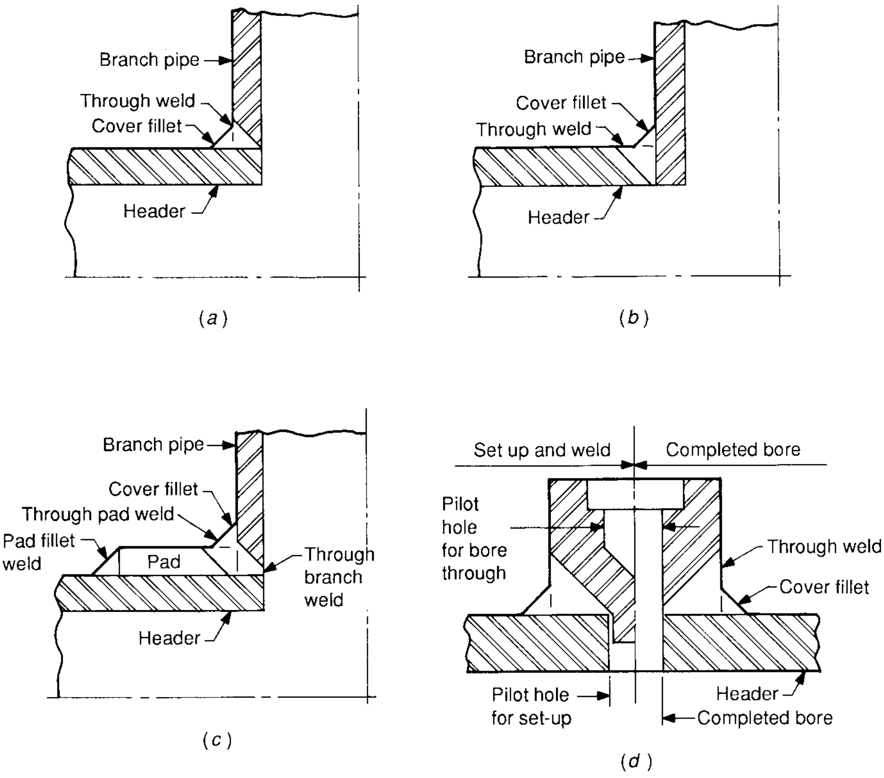


FIGURE A6.19 Types of branch nozzle construction. (*a*) Set-on; (*b*) set-through; (*c*) set-on with reinforcing pad; (*d*) special drill through socket weld coupling.

made from a plate product which may contain laminations, set-through construction is preferred.

Small nozzles are frequently made with socket welding or threaded couplings set on the header. In these cases it is difficult to assure complete root penetration, and specially designed couplings which permit drilling through the bore to remove the root of the weld are often used. See Fig. A6.19.

Welded-nozzle construction cannot be used at the full rating of the pipe involved, and suitability for particular pressure temperatures must be verified by component design methods found in Part B of this book. In all cases there must be a through thickness weld of the branch to the header. Where reinforcing pads are used, they should also be joined to the header by a weld through their thickness. See Fig. A6.19 for typical details. In designing headers with multiple outlet nozzles, sufficient clearance is needed between adjacent nozzles to provide accessibility for welding. Nozzles with reinforcing pads or flanges need greater clearance. PFI ES-7[31] gives suggested minimum spacings.

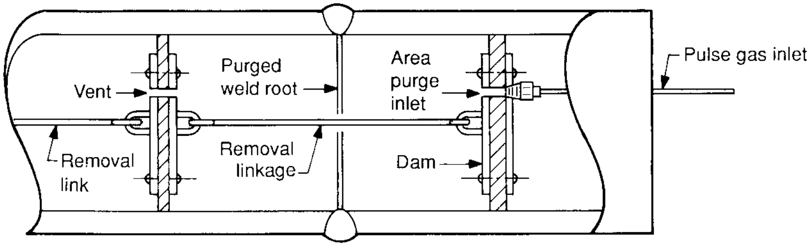
Root Pass Weldings. The integrity of any weld rests primarily with the quality of the root pass. In double-welded joints the root pass serves as a backing for passes welded from the first side. Before welding begins from the opposite side, the root area is usually removed to sound metal. In most cases, however, pipe welds must be made from one side only, and the inside surface of the root weld is not accessible for conditioning.

Backing Rings. The earliest solution to root pass welding was the use of a backing ring using the SMAW process. This usually assured good penetration and is still used for many applications. However, commercial rings used with nominal pipe dimensions may result in unwanted flow restriction, crevices for entrapment of corrosion products, and notch conditions which could result in cracking during service. Prior to the introduction of GTAW root welding, piping systems which required the highest possible quality were welded using counterboring of the pipe to close tolerances and machined backing rings. This reduced problems significantly, but the crack potential still remained. See PFI ES-1[32]

Open Butt Root Welds. In petrochemical services backing rings often could not be used, and the practice of open butt welding with shielded metal arc electrodes was and still is used. Welders require considerably more skill. Welding is most often performed with E-XX10 electrodes, which are more controllable than the low-hydrogen types but are also more prone to porosity.

GTAW Root Welds. The introduction of GTAW represented a breakthrough in root pass welding. Because of the greater expense involved, its application is usually limited to applications requiring high-quality root welds. The weld end bevels are carefully prepared by machining and counterboring where necessary to meet the close tolerances required. The joint involves butted or open lands, and the weld is made with filler metal added or with a preplaced consumable insert. The latter have a decided advantage in that they eliminate a good deal of the variability introduced by hand feeding of filler wire. Consumable inserts come in a variety of shapes, each requiring somewhat differing fit-up tolerances. See PFI ES-21. Some types can be used for root pass welding in lighter wall materials (½ in and less) without the need for counterboring. Depending on the service, the inside surface of the molten weld puddle is often shielded from oxidation by an inert gas inside the pipe contained between dams. See Fig. A6.20. A small, controlled, positive pressure on the backing gas can aid in better controlling the shape of the root inside diameter.

When the root pass is made by the GTAW process, the resulting finished weld is relatively thin. In depositing the second and third passes, the first pass may be



Dams consist of rubber gaskets between two flanges.

FIGURE A6.20 Typical shop purging arrangement.

remelted. As it resolidifies, it shrinks radially, resulting in a small concave depression on the inside of the weld. This condition is usually considered acceptable provided the resulting thickness through the finished weld is equal to or greater than the required minimum wall, and the concavity blends smoothly into the adjacent base metal.

GMAW Root Welds. Many fabricators and/or installers take advantage of the low penetrating power of GMAW in the short-circuiting mode to use it for open-butt root pass welding where the quality level of GTAW root pass welding is not required. The balance of the weld is made by other processes. Care must be taken to assure that unmelted wire does not penetrate the joint and remain.

Welding of Ferrous Piping Materials

Carbon Steels. Carbon steels are classed as P-No.1 by ASME Section IX. See Table A6.3. The vast majority of carbon steel pipe is used for services below 775°F (413°C). Joints are most often V bevels with commercial backing rings or open butt roots and are welded out with SMAW, SAW, GMAW, and FCAW. For services which require high quality, GTAW root welds with SMAW, SAW, and FCAW weld-outs are most prevalent. Most carbon steel filler metal is produced to weld 60,000- and 70,000-psi material. More often than not fabricators use the 70,000-psi filler for all carbon steel welding. For SMAW the most popular electrode is E-7018, although for open-butt root pass welding using SMAW, E-6010 is still the choice. FCAW welding is rapidly replacing SMAW because it can deposit at a much higher rate. Preheating and postweld heat treating are required depending on the carbon content and wall thickness. For typical preheat and postweld heat treatment requirements see Tables A6.4 and A6.7. When working to a specific code, be sure to use the requirements found in that code.

Carbon Molybdenum Steels. Carbon molybdenum steels are classed as P-No 3. Currently this material has very little use because of unfavorable experience with graphitization at temperatures over 800°F (427°C).

Chromium Molybdenum Steels. The chromium molybdenum steels are primarily used for service temperatures from 800 to 1050°F (427 to 565°C). They range from ½ Cr-½ Mo to 9 CR-1 Mo-V and are classed by ASME Section IX as P-No. 3, P-No. 4, and P-No. 5 A and 5 B. The preponderance of usage is in the 1¼ Cr-½ Mo-Si and 2¼ Cr-1 Mo grades. Welding usually consists of GTAW root welds with filler metal added or preplaced inserts. The balance of the weld is made by SAW for welds which can be performed in the 1G position and SMAW for fixed position welds. FCAW is rapidly overtaking SMAW for these materials also. See

TABLE A6.7 Some Typical Time and Temperature Cycles for Heat Treatment

		Holding temperature range*					
P no.	Heating rate	SR or T	N	A	CST	Minimum holding time at temperature	Cooling program
P-1	Above 800°F heat at a rate of 400°F/h divided by the thickness in inches but not faster than 400°F or less than 100°F	1100–1250°F	1600–1700°F	1500–1600°F	N/A	1 h/in of thickness but not less than 30 min or more than 2 h plus 15 min for each additional inch over 2 in	SR or T—Cool at 400°F/h divided by the thickness in inches but not faster than 400°F/h; need not be lower than 100°F/h down to 800°F N—Remove from furnace at normalizing temperature and cool in still air to 800°F; temper as necessary A—Furnace cool to 800°F at a rate of 400°F/h divided by the thickness in inches but not faster than 400°F/h; need not be slower than 100°F/h
P-3	Same as P-1	1100–1250°F	1600–1700°F	1500–1600°F	N/A		
P-4	Same as P-1	1300–1375°F	1725–1775°F	1625–1675°F	N/A	1 h/in of thickness but not less than 30 min or more than 5 h plus 15 min for each additional inch over 5 in	
P-5A & P-5B Gr.-1	Same as P-1	1300–1400°F	1725–1775°F	1625–1675°F	N/A		
P-8	Same as P-1	Not required	N/A	N/A	1900–2000°F	1 h/in of thickness but not less than 30 min or more than 2 h plus 15 min for each additional inch over 2 in	CST—Remove from furnace at holding temperature and quench in water to 300°F within 2 min

* SR = stress relief, T = temper, N = normalize, A = anneal, CST = carbide solution treatment

Source: Pullman Power Products Corporation.

Tables A6.4 and A6.7 for typical preheat and postweld heat-treatment requirements. Note that in B31.3 hardness limits are imposed to verify the adequacy of any heat treatment, and above-critical heat treatment may be necessary to attain the maximum hardness limit.

The 9Cr-1Mo-V material is a relatively recent addition to the list of chromium molybdenum steels for use in high-temperature service. Its great advantage over other chrome moly steels is its high-temperature strength. It has allowable stresses comparable with those of austenitic stainless steels. This results in a lesser wall thickness and consequently less weight to support and considerably less volume of filler material. A tighter line configuration can be anticipated because the lesser section modulous will result in smaller reactions at the terminals due to expansion loadings.

This material also has an advantage over austenitic stainless steels in that its coefficient of thermal expansion is less than that of the stainlesses, again resulting in lower end reactions for the same configuration.

On the down side, 9Cr-1Mo-V is typically a martensitic structure at room temperature and requires great care in bending, welding, and postbending and welding heat treatment.

For hot bending, a temperature of 1740 to 1920°F (950 to 1050°C) is preferred. Bending in the temperature range of 1560 to 1740°F (850 to 950°C) should be avoided. After hot bending, a normalize at 1900 to 1990°F (1040 to 1090°C) is required to put carbides back into solution. The normalize is followed by a tempering heat treatment between 1350 and 1440°F (730 and 780°C). Both are followed by cooling in still air.

Welding is extremely critical. The latest ASME Section II Part C, lists 9Cr-1Mo-V filler materials. SFA 5.5 lists E9018-B9 for SMAW electrodes, and SFA 5.28 lists ER90S-B9 for rods and electrodes for gas-shielded welding. Storage and handling of electrodes is very critical (see Filler Metals). Preheat and interpass temperatures and postwelding cooling should be scrupulously observed (see Preheat and Interpass Temperature). Postwelding stress relief is a necessity. The current ASME B31.1 Code requires a range of 1300 to 1400°F (700 to 760°C), but some literature indicates that a range of 1360 to 1440°F (740 to 780°C) may be more desirable for reasonable hardness and good ductility. The time at temperature should be 1 h per in of thickness, and heating and cooling rates above 800°F (427°C) should be limited to 100°F (55°C) per h.

Martensitic and Ferritic Stainless Steels. The martensitic and ferritic grades of stainless steels are not often encountered in piping systems. They are a group of steels with chromium contents ranging from 11.5 to 30 percent. Martensitic stainless steels are those which are capable of transformation to martensite under most cooling conditions and therefore can be hardened. Ferritic stainless steels on the other hand contain sufficient chromium and other ferrite formers such as aluminium, niobium, molybdenum, and titanium so that they cannot be hardened by heat treatment. ASME Section IX classes martensitic stainless steels as P-No.6 and ferritic stainless steels as P-No.7. The user should consult the *Welding Handbook*[16] for suggested welding processes and the applicable code for specific preheating and postweld heat-treatment requirements.

Austenitic Stainless Steels. Austenitic stainless steels are classed as P No. 8. Piping systems of austenitic stainless steels represent a fairly significant proportion of a fabricator's and/or installer's work, since they appear in nuclear power plants, chemical plants, paper mills, food processing facilities, and other applications where cleanliness and corrosion resistance are mandatory and even in fossil power plants where their high-temperature properties are needed. Most root welding is done by the GTAW process, and the inside of the root is protected by purging with argon, helium, or nitrogen to prevent formation of hard chromic oxides. GTAW is used for weld-out in lighter walls, and combinations of GTAW, SMAW, and SAW are used for heavier sections. Filler metal must contain some ferrite to preclude microfissuring as described in the section "Filler Metals." To minimize the precipitation of carbides (sensitization) during welding, interpass temperatures are usually limited to 300 to 350°F (150 to 175°C). Heat treatment after welding is not mandatory. For corrosion services, heating during fabrication could be detrimental since it would serve to enhance sensitization. The effects of sensitization can be mitigated by a carbide solution heat treatment as described in the section "Heat Treatment." Low-carbon grades of stainless steels welded with L grade electrodes are also used in services where sensitization can be a problem.

Low-Temperature Steels. The term *low-temperature steel* is applied to a variety of steels which exhibit good notch toughness properties at temperatures down to cryogenic levels.

The B31.1 and B31.3 Codes permit the use of most steel down to −20°F (−29°C). Below this, certain grades of carbon and nickel steel with good toughness and austenitic stainless steels are needed. Welding procedures and welding filler metals must be tested to assure suitability for the intended service. B31.3 gives details of such requirements. Root pass welding using GTAW, with SMAW and SAW weld-out, is commonly used. Some FCAW is used in the carbon steels and low-nickel steels.

A preheat of 200°F (95°C) is suggested by B31.3 for low-nickel steels followed by a postweld heat treatment consisting of a stress relieve at 1100 to 1175°F (600 to 630°C) when the wall exceeds ¾ in (19 mm). For 9 percent nickel steel a preheat of 50°F (10°C) and a stress relieve at 1025 to 1085°F (552 to 585°C) followed by cooling at a rate greater than 300°F/h (167°C/h) down to 600°F (316°C) is required.

Certain nonferrous materials are also suitable for low-temperature service. See the following section.

Welding of Nonferrous Metals

Aluminum. Aluminum and aluminum alloys have high thermal conductivity, high coefficients of thermal expansion, and high fluidity in the molten state. The predominant welding methods used for joining them are GMAW and GTAW, both manually and in automatic modes. Joint designs are much like those used for ferritic metals, except that the included angles are usually 60 to 75°, increasing to 90 or 110° for welding overhead. The root pass may be welded against a permanent aluminum backing strip or removable stainless-steel backup or with an open butt or consumable insert. Joint cleanliness is very important, so oil, grease, and dirt must be removed. For heavy oxide, wire brushing or chemical cleaning may be required. Preheating is normally not needed but may be required when the mass of the parts is large enough to conduct the heat of welding away from the joint faster than it can be supplied by the arc. Depending on the welding process used, as the weld thickness increases from about ¼ to 1 in (19 to 25 mm), a preheat of 200 to 600°F (95 to 316°C) may be required. Since the properties and tempers of certain alloys may be affected, care should be exercised when preheat is applied. Shielding gases are usually helium or argon. For critical applications and heavier sections a mixture of 75 percent helium, 25 percent argon is recommended. Heat treatment after welding is not required.

It is important to remember that the annealing effect of the heat of welding can reduce the strength level of cold-worked and heat-treatable alloys. In this case the allowable stress value for the material in the annealed condition should be used for design. An exception to this can be made in the case of heat-treatable materials when the finished weldment is subjected to the same heat treatment which produced the original temper and both the base metal and weld joint are similarly affected.

Aluminum and aluminum alloys are suitable for service temperatures down to −452°F (−269°C). See B31.3 for information on this subject.

Copper and Copper Alloys. Although copper and copper alloys can be welded by other processes, GTAW welding is commonly applicable for all-position welding of most copper and copper alloys. GMAW with pulsed current can also be used for some alloys. Shielding gases may be argon, helium, or mixtures thereof. Argon is preferred for walls to ⅛ in (3 mm), but a 75 percent helium, 25 percent argon mixture is most often used for heavier walls and weld positions other than flat (1G).

Like aluminum, the coppers have high thermal conductivity and high coefficient of thermal expansion. Accordingly, preheating is recommended to compensate for heat loss at the joint due to the metal mass and to reduce distortion. Welding current should not be used to compensate for heat loss. The degree of preheat is a function of alloy, welding process, and metal mass. More heat input is needed for the pure coppers, with decreasing amounts needed as the alloy content increases. Preheat should increase with wall thickness, from about 200°F (95°C) for ¼-in (6 mm) wall increasing to 750°F (400°C) minimum for walls ⅝ in (16 mm) and over. Surface cleanliness is very important, and some alloys require a chemical cleaning to remove oxides. Copper-nickel alloys are susceptible to hot cracking if sulfur is present.

The heat of welding will soften the HAZ of cold-worked material, and it will be weaker than the base metal. When precipitation-hardenable alloys are used, it is recommended that welding be done on base metal in the annealed condition and the entire weldment be given the precipitation-hardening heat treatment. For detailed information refer to the *Welding Handbook*,[16] the *Metals Handbook*,[20] or contact the Copper Development Association.

Many coppers are suitable for services down to −325°F (−199°C), See ASME B31.3.

Nickel and Nickel Alloys. Nickel and its alloys can be welded by SMAW, GTAW, and GMAW. SAW is limited to certain compositions. Welding is similar to austenitic stainless steels except that the molten metal is more sluggish and does not wet as well. Larger groove angles may be required. Preheat is not required, but welding at temperatures below 60°F (16°C) in the presence of moisture is not recommended. A low interpass temperature is suggested. For GTAW welding shielding gas is normally argon, but helium or an argon-helium mix may be used. The inside surface of GTAW root welds should be shielded with an inert gas. GMAW in the spray, pulsed, globular, or short-circuiting modes may be used with argon or argon-helium mixtures as shielding. Postweld heat treatment is not usually required. Many nickel and nickel alloys may be used down to −325°F (−199°C). For more detailed information refer to the *Welding Handbook*,[16] the *Metals Handbook*,[20] and ASME B31.3.

Titanium. Titanium and its alloys are normally welded using the GTAW and GMAW processes. It is vital that the HAZ and molten metal be protected from the atmosphere by a blanket of inert gas during welding. Most welding is done in a protective chamber purged with an inert gas or by using trailing shields. Precleaning is extremely important. Use of degreasers, stainless steel wire brushes, or chemical solutions may be required. Preheating or postweld heat treatment are not normally required. See the *Welding Handbook*[16] and the *Metals Handbook*.[20]

Dissimilar Metals. Until now we have discussed welding where both items being joined are essentially the same material and are joined with a filler metal of similar chemistry and physical properties. Occasions arise where metals of different chemical composition and physical properties must be joined.

In joining dissimilar metals, normal welding techniques may be employed if the two base metals have melting temperatures within about 200°F (95°C) of each other. Otherwise different joining techniques are required.

In designing a welding procedure for dissimilar metals, a great many factors must be considered. Service conditions such as temperature, corrosion, and the degree of thermal cycling may apply. The effects of dilution of the two base metals by the filler and each other must be evaluated to assure a sound weld with suitable chemical, physical, metallurgical, and corrosion-resistant properties. Similarly, preheat and postweld heat treatment requirements for one base metal may not be suitable for the other.

It is usually necessary to qualify a separate welding procedure for the particular combination of base metals and filler material. ASME Section IX should be consulted for specifics.

As a general rule, when welding within a family such as ferritic to ferritic, austenitic to austenitic, or nickel alloy to nickel alloy, the filler metal may be of the same nominal composition as either of the base metals or of an intermediate composition. The filler metal normally used to weld the lower alloy is most often preferred.

The previous advice may not always hold true. It has been noted that when welding P 22 (2¼Cr-1Mo) to P 91 (9Cr-1Mo-V) using 2¼Cr filler metal at high temperatures, carbon migration from the 2¼Cr weld metal to the 9Cr base metal can produce a carbon-denuded zone at the interface, resulting in a weakened area. One recommendation is to "butter" the 9Cr side with a 5Cr filler metal, heat-treat the buttered segment, and complete the weld with 2¼Cr. Bear in mind that the 5Cr filler may not have high-temperature properties similar to the 2¼Cr, and design the weldment accordingly.

In welding dissimilar materials, selection of preheating and postweld heat treatment requires a great deal of care. What is desirable for one metal may be detrimental to another. Some compromise may be required.

Establishing a welding procedure for welding ferritic to austenitic steels requires careful consideration of the service conditions. For moderate service temperatures (below 800°F or 427°C), where the thickness of the ferritic side does not require postweld heat treatment, austenitic stainless steel electrodes are often the choice. Some prefer electrodes such as type 309 or 310 because of their higher chrome content. Because of the thickness involved, the ferritic member may require some type of postweld heat treatment. In this case the preferred method is to butter the ferritic weld surface with a nickel-chrome-iron (NiCrFe) filler metal such as ERNiCrMo-3 (see ASME Section II Part C SFA-5.14) and postweld heat-treat the buttered section as required for the ferritic composition. The buttered section is then prepared for welding, set up with the austenitic side, and the weld between the butter and austenitic base metal is completed with NiCrFe filler metal without subsequent postweld heat treatment. See Fig. A6.21.

For high-temperature service (above 800°F or 427°C) the buttering procedure just described is also recommended. There is a difference in coefficients of expansion between the ferritic and austenitic metals. This difference will result in expansion stresses above the yield point at the weld juncture while at operating temperature. At higher temperatures there is also greater probability of diffusion of carbon from the ferritic side to the austenitic side. The NiCrFe "butter" minimizes the carbon diffusion problem and has an expansion coefficient which is intermediate between the two base metals, thus reducing but not eliminating the thermal stress at the interface. Where a transition from ferritic to austenitic steels is required in high-

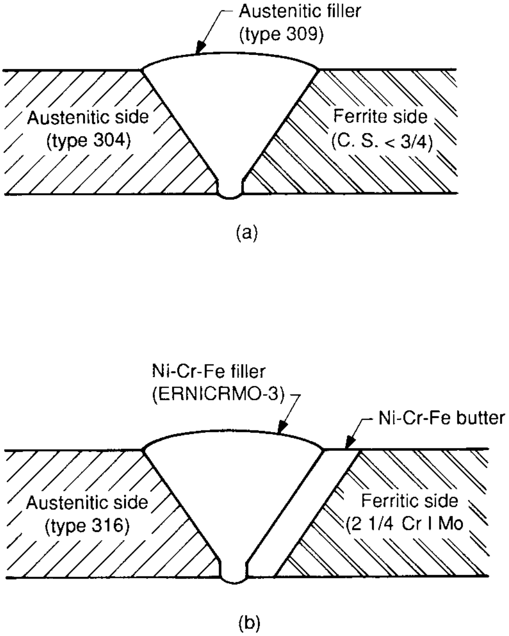


FIGURE A6.21 Dissimilar metal welds. (*a*) For moderate temperature service; (*b*) for high-temperature services or where stress relief on the ferritic side is required.

temperature applications involving cyclic services, a transition piece of a high-nickel alloy such as UNS N06600 with two welds is often used to reduce thermal fatigue damage.

In welding nonferrous metals to ferrous or other nonferrous metals, a filler metal with a melting point comparable to the lower melting point base metal is usually recommended.

Nickel and nickel alloys are invariably welded to ferrous metals with nickel-alloy filler metals. Sulfur embrittlement can be a problem with nickel to ferritic welds, just as it is in nickel-to-nickel welds. Copper-nickel and nickel-copper alloys should not be joined with filler materials containing iron or chromium since hot cracking may result.

Copper and copper alloys can be welded to carbon steel with silicon bronze or aluminum bronze electrodes, but the preferred method is to butter the carbon steel side with nickel and weld the copper to the nickel butter with nickel filler. This will preclude hot cracking of the copper because of iron dilution. The copper side may require preheat. Copper can easily be welded to nickel, copper-nickel, or nickel-copper filler metal. When welding nickel alloys which contain iron or chromium to copper, the nickel alloy should be buttered with nickel.

Aluminum and titanium generally cannot be welded to ferrous or other nonferrous metal using currently available welding procedures, and special joining procedures must be employed.

Clad, Metal-Coated, and Lined Pipe. There are instances when it is economically desirable to construct a piping system from relatively inexpensive material but with an interior surface having corrosion- or erosion-resistant properties. Clad pipe may be made by seam welding of clad plate, by weld metal overlay of the inside surface, or by centrifugal casting of a pipe with two metal layers. Lined pipe is made by welding a linear, sometimes as strips, to the inside surface of the pipe. Metal-coated pipe is made by dipping, metal spraying, or plating the entire pipe.

Before choosing construction which requires welding of clad, lined, or metal-coated pipe, such factors as filler metal compatibility, filler metal strength relative to the base metal strength, dilution of base metal into the finished weld, and need for postfabrication heat treatment must be considered. Because it is not possible to cover the great many combinations of base metals and cladding, lining, or metal coatings, some examples of the more common applications will be given.

For corrosion services, a carbon steel base material, clad or lined with austenitic stainless steel, is often used. The cladding is usually about 3⁄32 to 5⁄32 in thick. Where the inside of the weld is accessible, the preferred method is to weld the base metal from the outside with carbon steel filler metal, back-gouge the root from the inside, and weld the root from the inside with two or more passes of austenitic filler metal to minimize dilution from the base metal. See Fig. A6.22*a*.

Where the inside surface is not accessible, a backing strip of the same composition as the cladding, fillet welded to the cladding on the upstream side may be used. The root weld between the two clad surfaces and the austenitic backing strip is then made with austenitic filler metal. The root weld can also be made with the GTAW process using austenitic filler or preplaced inserts. The carbon steel should be removed for a sufficient distance back to preclude dilution into the root weld. In most instances, the balance of the weld is usually made with austenitic filler metal since it is not good practice to deposit carbon steel or low-alloy steel directly against the stainless steel deposit. See Fig. A6.22*b*. In some cases, nickel-base alloys are used for cladding where high-temperature corrosion is involved. The joints may be treated much like the austenitic cladding, except that appropriate nickel-base filler metals are used.

Some services require the use of carbon steel pipe nickel plated on the inside surface. Since the plating is relatively thin, different approaches are needed. First, as much fabrication as possible should be done prior to plating. For joints to be welded after plating, the ends to be prepared for welding should be buttered with nickel filler metal and machined to the required contour prior to plating. The root weld is made using the GTAW process with nickel filler metal. See Fig. A6.22*c*.

Some occasions require the use of aluminized pipe. Steel pipe is prefabricated and coated with aluminum by immersion in a bath of molten aluminum or by metal spray. Where the inside of the weld will not be accessible for metal spray, one method of joining is to counterbore the ends and use a solid machined backing ring which is fit and welded into one side of the joint prior to coating. After coating, the weld is made using an appropriate base metal process and filler, taking care not to blister the aluminum coating on the underside of the backing ring.

Galvanized steel pipe is often used for external corrosion applications. Since welding of galvanized pipe releases toxic vapors and since the welded area most often cannot be regalvanized, welding of galvanized pipe is not recommended. It is preferable that the assemblies be fabricated with provisions for mechanical joining in the field and then galvanized.

For services involving erosion, carbon steel pipe is often lined with cement or

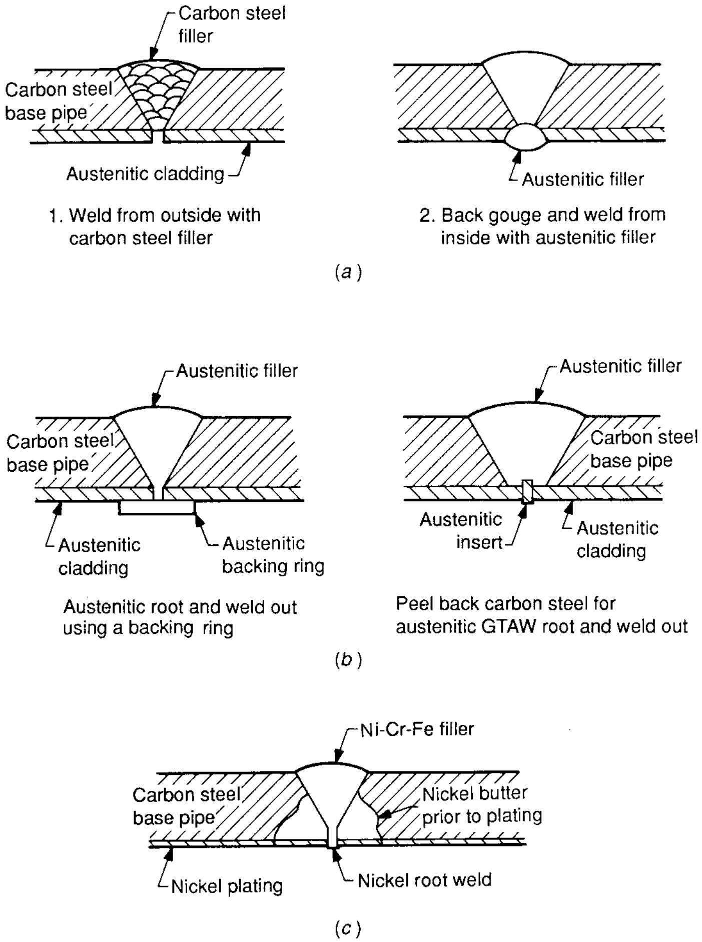


FIGURE A6.22 Examples of welding clad, lined, and plated pipe. (*a*) Clad pipe welded from both sides; (*b*) clad pipe welded from one side only; (*c*) nickel-plated pipe.

some type of abrasion-resistant material which cannot be welded. In this case the joints are butted together to minimize the gap between the adjacent linings. The weld is then made between the two carbon steel weld bevels, recognizing that full penetration through the carbon steel joint may not be achieved and that additional thickness may be necessary for strength. The gap between the adjacent linings is usually not a problem if only erosion is present.

Brazing and Soldering

Brazing. For services involving the ASME Boiler and Pressure Vessel Code or the B31 Code for Pressure Piping, brazing procedures and brazers must be qualified in accordance with ASME Section IX similar to welding procedures and welders. See the section ''Procedure and Personnel Qualification.''

There are a great many types of brazing processes. In establishing a brazing procedure, consideration must be given to the ability of the filler metal to produce suitable physical properties, its melting point and wettability, possible base metal and filler metal interactions, loss of base metal properties, increased sensitization to corrosion, increased hardness in the base metal due to brazing temperature, and the need for postbrazing heat treatments.

Since most piping materials can be welded, the use of brazing for joining is rather limited. It is most often used for joining coppers and for combinations of metals which cannot be welded.

Brazing is a process wherein the base metals do not melt, the filler metal has a liquidus above 840°F (450°C), and the filler metal wets the base metal and is drawn into the joint by capillary action.

Although butt or scarf joints can be used, a lapped joint with an overlap of 3 times the thickness of the thinner member gives the best joint efficiency and ease of fabrication. It should be noted that typical copper or brass fittings have a depth of socket based on the strength of tin-lead solders. When brazing is used, only a small percentage of that depth is needed. Required clearance between the faying surfaces usually vary from 0.001 to 0.010 in (0.025 to 0.25 mm) depending on the filler and flux combination used during the operation. The flux melts upon application of heat and is displaced by the molten filler metal. Flux residue should be removed after the operation is complete. Silver, copper-phosphorus, and copper-zinc filler metals are most often used for copper brazing.

Torch brazing is commonly used for fabrication and installation of copper piping systems. For torch brazing, the type of fuel gas selected is a function of the melting temperature required to melt the filler metal. For piping joints NPS 2 (DN 50) and larger, use of a second torch to preheat may be desirable.

In brazing metals with differing coefficients of expansion, it is preferable that the metal with the higher expansion coefficient form the socket and the metal of the lower expansion coefficient form the pipe or tube. Clearance between the parts at room temperature must be adjusted so there will be a suitable clearance at brazing temperature. On cooling, the greater contraction of the socket will put the joint in a compressive stress state.

Soldering. Unlike welding and brazing, ASME Section IX has no requirements for qualification of soldering procedures or personnel. Soldering is much like brazing in that the base metals are not melted, the faying surfaces are wetted by the filler, and the filler is drawn into the joint by capillary action. However, the melting point of the filler metal is lower than 840°F (450°C) usually between 450 and 500°F (230 and 260°C). Since the strength of soldering filler metals is considerably less than that of brazing fillers, a longer overlap is required to develop a joint equal to base metal strength. A clearance of about 0.003 in is preferred for optimum strength.

A good soldered joint depends again on the cleanliness of the faying surfaces. Fluxes are used to assist in the wetting action by removing tarnish films and to prevent oxidation. Rosin fluxes and organic fluxes are used for most materials. Inorganic fluxes may be required for certain other materials that can be soldered, while in some cases precoating of the material with a surface that can be soldered may be required. Most piping applications use tin-lead solders. These range in composition from 5 percent tin, 95 percent lead to 70 percent tin, 30 percent lead, with 50 percent tin, 50 percent lead the most common. Tin-antimony and tin-silver solders are also frequently used. For soldering aluminum, tin-zinc and zinc-aluminum are used.

For additional information refer to the *Welding Handbook*[16] and *The Theory and Technique of Soldering and Brazing of Piping Systems.*[33]

Heat Treatment

Purpose. Heat treatment during piping fabrication is performed for a variety of reasons (i.e., to soften material for working, to relieve fabrication stresses, to restore metallurgical and physical properties, etc.). During fabrication, ferritic steels undergo phase changes during heating and cooling, while the austenitic stainless steels and nonferrous piping materials do not; consequently differing criteria must be applied.

Ferritic Steels. Ferritic steels undergo a phase change on heating and cooling during fabrication operations because their principal component (iron) is allotropic; that is, it undergoes a change in crystalline structure with temperature. At room temperature iron favors a body-centered cubic (BCC) structure called *alpha iron*, but on heating to 1670°F (910°C) it changes to a face-centered cubic (FCC) structure called *gamma iron* and subsequently at 2534°F (1390°C) it reverts to a BCC called *delta iron*. The addition of carbon to the iron to form steel and additions of other elements such as chromium, manganese, molybdenum, and nickel to form alloys modify the temperatures at which transformation occurs and the manner in which the crystalline structure forms into grains.

As an example, a melt of 0.30 percent carbon steel will first begin to solidify as delta iron and a liquid, then at about 2680°F (1479°C) to an interstitial solid solution of carbon in gamma iron called *austenite*. At about 1500°F (815°C) this will transform into a mixture of austenite and ferrite, which at 1333°F (721°C) becomes ferrite and pearlite. Ferrite is alpha iron which contains small amounts of carbon (up to a maximum of about 0.02 percent) in solid solution. The excess carbon not in solid solution with the ferrite forms as iron carbide (Fe_3C) or cementite. The cementite forms as thin plates alternating with ferrite. This structure is known as *pearlite*.

The temperatures at which the transformations occur are called critical temperatures or transformation temperatures. The lower critical temperature, usually designated A_1, is that point on heating where the BCC ferrite and pearlite phase begins to transform to FCC austenitic structure, and the upper critical temperature, A_3, is the temperature at which the transformation is complete. Between these two points the structure is a mix of ferrite-pearlite and austenite. These temperatures are of importance in postbending and postwelding heat treatments as well as qualification of welding procedures.

The critical temperatures are a function of chemical composition and as such will vary with alloy. As an example, for 9Cr-1Mo-V, the lower critical is located between 1525 and 1560°F (830 and 850°C), and the upper critical is between 1650 and 1725°F (900 and 940°C). Some approximate methods of calculating critical temperature are found in *Welding Metallurgy*[34] and *The Making, Shaping and Treating of Steel.*[35] Some approximate lower critical temperatures are given in Table A6.8.

Critical temperatures are affected by heating and cooling rates. An increase in heating rate will serve to increase the transformation temperatures, while an increase in cooling rate will tend to depress them. The more rapid the rate of heating or cooling, the greater the variation from the critical temperature at equilibrium conditions. Most sources will indicate the lower and upper critical temperatures on heating as A_{c1} and A_{c3}, respectively, and the upper and lower on cooling as the A_{r3} and A_{r1}, respectively. In the case of our 0.30 percent carbon steel, cooling from the austenite phase through the critical range at a rate of 50°F/h (28°C/h) or less will result in the soft, ductile ferrite-pearlite structure. On the other hand, extremely

TABLE A6.8 Approximate Lower Critical Temperatures

Material	Approximate lower critical temperature [°F (°C)]
Carbon steel	1340 (725)
Carbon molybdenum steel	1350 (730)
1¼ Cr–½ Mo	1430 (775)
2¼ Cr–1 Mo, 3 Cr–1 Mo	1480 (805)
5 Cr–½ Mo	1505 (820)
9 Cr–1 Mo	1490 (810)

Source: From ASME B31.1 1995 ed.

rapid cooling from the austenite phase down to temperatures 600°F (316°C) or lower can result in an extremely hard structure called *martensite*. This is because the austenite FCC crystals did not have time to transform to BCC ferrite and cementite.

Heat treatments which are applied to ferritic steels are related to the critical temperatures and depending on which is applied will have differing results. These are annealing, normalizing, normalizing and tempering, and stress relieving. See Fig. A6.23.

Annealing is used to reduce hardness, improve machinability, or produce a more uniform microstructure. It involves heating to a temperature above the upper critical or to a point within the critical range, holding for a period of time to assure temperature uniformity, then following with a slow furnace-controlled cooling through the critical range.

Normalizing is used to refine and homogenize the grain structure and to provide more uniform mechanical properties and higher resistance to impact loadings. It involves heating to a temperature above the upper critical temperature, holding for a time to permit complete transformation to austenite, and cooling in still air from the austenitizing temperature.

A normalized structure may be pearlitic, bainitic, or even martensitic depending on the cooling rate. If there is a concern for excessive hardness and attendant low ductility, a tempering treatment may follow the normalizing treatment. Tempering involves heating to a temperature below the lower critical and slowly cooling to room temperature, much like a stress relief. The degree of tempering depends on the tempering temperature selected. The higher the tempering temperature, the greater the degree of softening.

A stress-relieving heat treatment is primarily intended to reduce residual stresses resulting from bending and welding. It involves heating to a temperature below the lower critical; holding for a predetermined time, depending on thickness and material, to permit the residual stresses to creep out; and then slowly cooling to room temperature.

Some typical time-temperature cycles are shown in Table A6.7.

Austenitic Stainless Steels. Austenitic stainless steels do not undergo phase changes like the ferritic steels. They remain austenitic at all temperatures and so heat treatments usually do not apply. When austenitic stainless steels are to be used in corrosive services, cold working and heating for bending may significantly lower their corrosion resistance. Cold working may result in residual stresses, and heating operations can result in sensitization. Both factors contribute to intergranular stress corrosion cracking (IGSCC). When austenitic stainless steels are heated

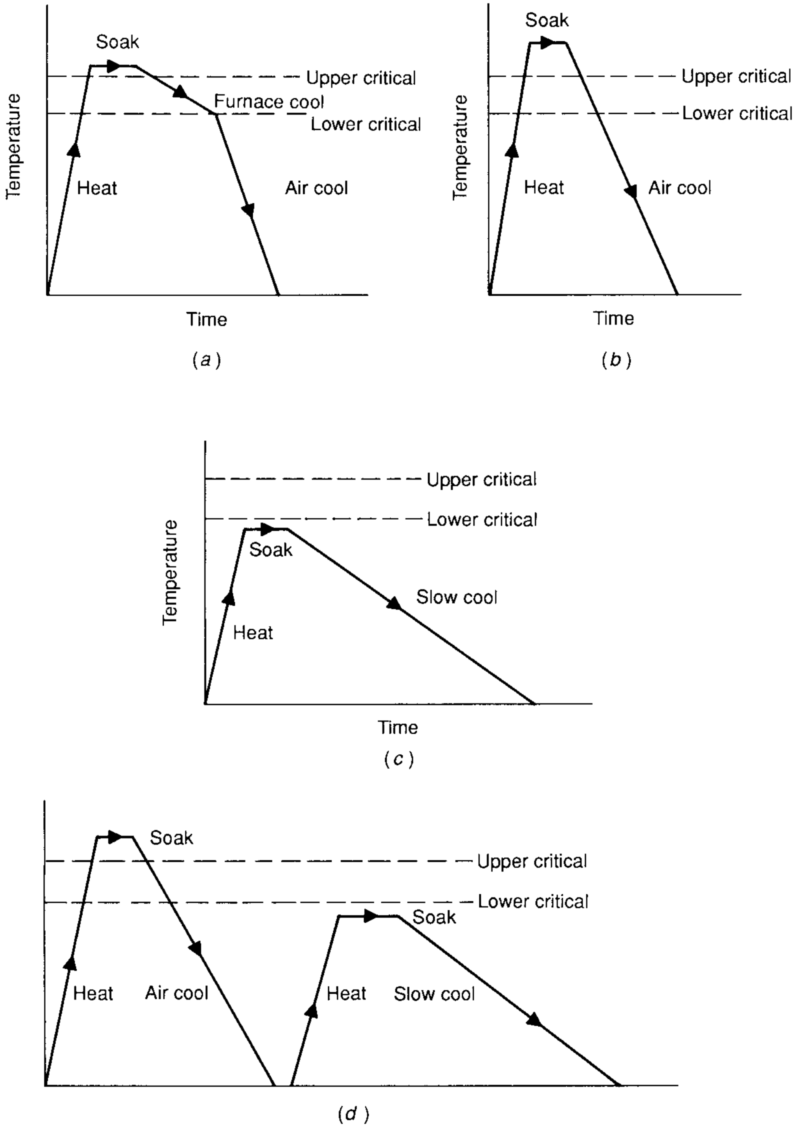


FIGURE A6.23 Heat treatment cycles. (*a*) Anneal; (*b*) normalize; (*c*) stress relief; (*d*) normalize and temper.

in the range of about 800 to 1600°F (430 to 870°C), carbon in excess of about 0.02 percent will come out of solution and diffuse to the grain boundaries where it will combine with adjacent chromium to form chromium carbide ($Cr_{23}C_6$). This phenomenon is called *sensitization*. These grain boundaries are then preferentially attacked by corrosive media. The heat treatment often applied to cold-worked and sensitized stainless steels to restore corrosion resistance is a carbide solution heat treatment. In this procedure, the material is heated to a temperature above the sensitization range, usually about (1950 to 2100°F (1065 to 1150°C), and held there sufficiently long to permit the carbides to dissolve and the carbon to go back into solid solution. The material is then removed from the furnace and rapidly cooled through the sensitization range, preferably by quenching in water. The rapid cooling does not give the carbon sufficient time to come out of solution, and corrosion resistance is restored to the sensitized area.

Obviously carbide solution heat treatment is limited by the furnace size and quenching facilities. It is most freqently applied to bends but is also useful in reducing sensitization and residual stresses in welds.

Nonferrous Materials. Bending and forming of nonferrous materials may result in undesirable work-hardening. Some nickel alloys may be subject to carbide precipitation when hot bent or formed. Materials that can be hardened by precipitation require other considerations. Depending on the final use, it may be desirable to perform some type of postbending or forming heat treatment. Because of the great many new materials being developed and used, it is suggested that the user contact the material manufacturers or material associations for their recommendations on the specific material and service.

Heat Treatment Methods. Shop heat treatments are most often carried out in specifically designed heat treatment furnaces, but local stress relieving of welds may also involve induction, resistance, or torch heating.

Above critical heat treatments, such as annealing, normalizing, and normalizing and tempering for ferritic steel and carbide solution heat treatment for austenitic stainless steels, are performed in large heat-treatment furnaces. These same furnaces are also used for stress-relieving heat treatments of ferritic steels. Such furnaces are generally fired with natural gas, propane, or low-sulfur oil. Depending on their design, they may attain temperatures up to 2300°F (1260°C) which covers the entire spectrum of temperatures commonly encountered in piping applications. Heating and cooling rates and holding temperatures are automatically controlled. Larger furnaces may have two or more zones, each independently controlled. Records of furnace zone temperatures and material temperatures are obtained using recording potentiometers.

When assemblies are too large or furnaces are not available, local stress relieving of individual welds may be accomplished in the shop using electrical induction, electrical resistance, or gas torch heating.

Induction equipment involves alternating current frequencies of the order of 60 to 400 Hz. Induction generates heat within the wall of the pipe. This has the advantage of a more uniform temperature through the thickness with greater uniformity at the lower frequencies. The heat treatment cycle is controlled automatically with thermocouples attached directly on or adjacent to the weld. The weld and thermocouple are covered with insulating material. The induction field is generated in copper cables or solid or water-cooled copper coils external to the insulation. See Fig. A6.24.

Resistance heating involves the use of direct current in suitable lengths of nichrome heating wire. Various configurations and sizes of prefabricated heating elements consisting of heating wires separated by ceramic beads are available

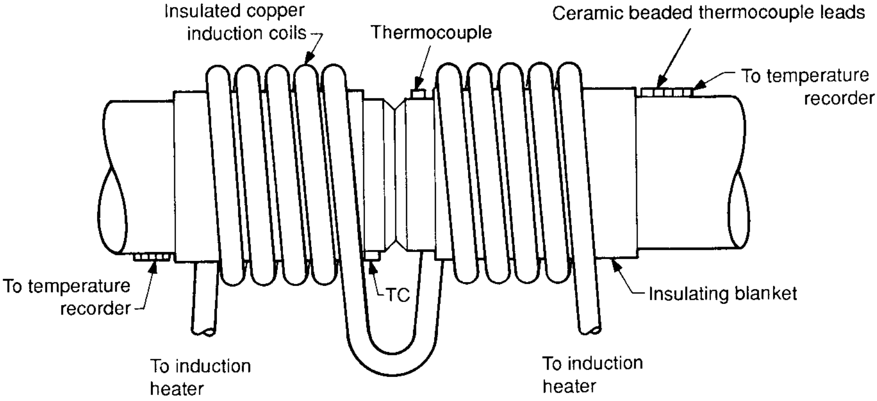


FIGURE A6.24 Setup for preheat, maintenance of preheat during welding, and stress relief using induction heating.

commercially. Depending on the size, wall thickness, and desired heating temperature, multiple heating units and combinations of elements may be needed. The weld and heating elements are covered with insulating blankets to retain the heat. Since heating is from one side, a somewhat wider heating band on the outside may be needed to assure that the inside of the pipe attains the required temperature. Thermocouples attached directly to the weld or adjacent to it are used to control heating, holding, and cooling temperatures.

Torch heating can often be used for stress relieving, but where controlled heating and cooling rates are mandated, it may be less than satisfactory. Single torches may be used for pipe up to about NPS 3 (DN 80), but ring burners are needed for larger sizes.

Exothermic heating has been used in the field and is discussed in the section ''Installation.''

Heat Treatment Considerations

Furnace Heat Treatment. To assure that heat treatments attain the results intended (i.e., correct heating and cooling rates, desired holding temperature in all parts, etc.), it is very important that all controlling and recording instruments be calibrated on a regular basis. The furnace should be inspected and a temperature survey made to assure that all locations within it are capable of attaining and maintaining specific temperatures within some reasonable tolerance. This is particularly important if the zone temperatures are used as the basis for acceptance of the heat treatment. If there is any concern, it might be advisable to attach thermocouples directly to the parts being heat-treated.

When piping subassemblies are placed in the furnace, they should be supported to permit exposure of the underside to the radiant and convection heating surface. Supports should be located so as to avoid sagging. Care should be taken to avoid any flame impingement directly on surfaces being heat-treated.

The ends of assemblies being heat-treated should be closed but not sealed to minimize oxidation of the inside surfaces. Occasions may arise where special surface finishes on the pipe inside surface or on flow meter sections could be adversely affected by oxidation caused by heat treatment. In such cases the inside of the assembly can be purged with an inert gas to minimize oxidation.

Assemblies should be so placed as to assure the uniform application of heat. Heating and cooling rates must be selected to assure heating through the full thickness and to minimize distortion caused by uneven heating. The faster the rate of heating or cooling, the more probability of distortion. Assemblies with massive flanges, fittings, or other unusual configurations should be treated more carefully than those with butt welds only. Many of the codes have specified heating and cooling rates which are considered reasonable.

Local Heat Treatment. When an assembly is too large for a furnace to accommodate, it may be fabricated in sections which are individually furnace heat-treated and later joined by welding. The final butt welds may then be locally heat-treated in the same fashion as field welds. The most common practice is the use of induction or resistance heating. When preheating is an essential part of the welding operation, the induction or resistance equipment can be used for preheating, maintaining preheat during welding, and, finally, stress relieving.

A proper stress-relieving operation will assure that the weld and HAZ through the full thickness will attain the required temperature for the required time. The B31.1 Code requires that the heated band be at least 3 times the thickness of the thickest part being joined. With induction or resistance heating the heating elements themselves often have greater coverage. Depending on the massiveness of the joint being heated, one or more pieces of heating equipment may be needed. Controlling and recording thermocouples are located on or adjacent to the weld. Usually locally heat-treated shop welds are in the 5G position (pipe horizontal, weld vertical). For small pipe sizes, a single thermocouple located at the 12 o'clock position may suffice, but for larger diameters and heavier walls at least two and preferably four, located at 90° intervals, should be employed to assure uniformity of heating.

Judicious use of insulating material should be employed to minimize heat loss. When joining parts of differing masses, concentrate more heating effort on the more massive part.

If it is necessary to locally stress-relieve a branch connection, not only the branch weld itself but the entire circumference of the header for a distance of at least 2 times the header thickness on either side of the branch should be heated. Heating of the weld alone, while resulting in a satisfactory stress relief, could distort the header significantly.

Heating and cooling during local stress relief of pipe to pipe joints can be more rapid than for furnace applications since there is less chance of distortion unless, of course, the heating is not applied uniformly. Ends of the assembly should be closed but not sealed to reduce heat loss on the inside surface due to air flow. The main concern is assurance that the inside surface of the weld attains the required temperature for the required time.

Local stress relieving with torches or gas ring burners can be effectively employed but must be limited to situations where controlled heating and cooling rates are not a factor.

Code Requirements

Postbending and Postforming Requirements. The designer of the piping system should specify the type of heat treatment required to assure appropriate physical, metallurgical, or corrosion-resistant properties. As an example, a normalize or normalize and temper may be required to assure certain notch toughness properties for nuclear or low-temperature applications, or a carbide solution heat treatment for cold-worked austenitic stainless steel may be required to preclude IGSCC. This should be agreed upon well before any fabrication starts.

The codes have certain mandatory heat treatment requirements which must be observed as a minimum, normally a stress-relieving treatment. Such heat treatment is usually in accordance with the postweld heat treatment tables given in the applicable code. Differing requirements apply depending on whether the bending or forming was performed hot or cold. According to B31.3, cold bending is performed at a temperature below the transformation range (below the lower critical), and hot bending is performed at a temperature above the transformation range (above the upper critical). B31.1 and ASME Section III make the break between hot and cold bending at a temperature 100°F (38°C) below the lower critical.

B31.3 requires heat treatment after cold bending when (1) specified in the engineering design, (2) the calculated elongation will exceed 5 percent for materials requiring notch toughness properties, and (3) the calculated elongation will exceed 50 percent of the specified minimum elongation indicated in the material specification for P-No.1 through P-No.6 materials. For hot bending and forming, heat treatment is required for all thicknesses of P-Nos.3, 4, 5, 6, and 10A materials.

B31.1 and ASME Section III on the other hand require heat treatment after bending or forming in accordance with the postweld heat treatment table of the applicable code for P-No.1 materials with a nominal wall thickness exceeding ¾ in unless the bending or forming was completed above 1650°F (900°C). All ferritic alloy materials of NPS 4 (DN 100) or larger or with a nominal wall thickness of ½ in or greater which are hot bent or formed must receive an annealing, normalizing and tempering, or a tempering heat treatment to be specified by the designer, or if cold bent or formed, the heat treatment at the required time and temperature cycle specified in the postweld heat treatment table for the material involved.

The codes have no requirements for postbending or forming heat treatments of austenitic stainless steels or nonferrous materials.

Postwelding Heat Treatment Requirements. Before applying any post-welding heat treatment (PWHT), it should be noted that for work under ASME Section IX, postwelding heat treatment is an essential variable for welding procedure qualification. For ferritic materials there are five possible conditions of heat treatment, each requiring separate qualifications. These are:

1. No PWHT
2. PWHT below the lower critical temperature (stress relief)
3. PWHT above the upper critical temperature (normalize or anneal)
4. PWHT above the upper critical temperature, followed by heat treatment below the lower critical temperature (normalize and temper)
5. PWHT between the upper and lower critical temperatures.

For other materials, two conditions apply: no PWHT or PWHT within a specified temperature range.

Accordingly, for shop work, it may be necessary to qualify welding procedures for several possible heat-treatment situations. For field work only the no heat treatment or stress-relieving situations will normally apply.

When required by the codes, heat treatment consists of a stress-relieving operation. Other heat treatments such as annealing, normalizing, or solution heat treatment may be applied but are not mandatory. However, the welding procedure must have been qualified for the heat treatment applied.

Each code has its own definition regarding governing thicknesses, its own exemptions, differing temperature and holding requirements, heating and cooling rates, etc., reflecting the differing concerns and needs of individual industries. The codes are also constantly evolving as the committees obtain and review new data. Accordingly, the reader should refer to the applicable edition of the code of interest for requirements.

At the time of this writing, the following is a comparison of the heat treatment requirements for carbon steel materials.

B31.1 requires heat treatment of P-No. 1 Gr.Nos. 1, 2, and 3 in the temperature range of 1100 to 1200°F (600 to 650°C) for 1 h/in (1 h/25 mm) of thickness for the first 2 in (50 mm) plus 15 min for each additional inch over 2 in (50 mm), with a 15-min minimum. Exempted are welds with a nominal thickness of ¾ in (19 mm) or less, and a 200°F (95°C) preheat must be applied when either of the base metals exceed 1 in (25 mm). The nominal thickness is defined as the lesser of the thickness of the weld or the thicker of the base metals being joined at the weld. The thickness of the weld is further defined as the thicker of the abutting edges in a groove weld, the throat of a fillet weld, the depth of a partial penetration weld, and the depth of the cavity for repair welds. Thickness as it relates to branch welds is a function of the header thickness, the branch thickness, and reinforcing pad thickness.

B31.1 also requires controlled heating and cooling at temperatures above 600°F (316°C). The rate shall not exceed 600°F/h (335°C/h) or 600°F/h (335°C/h) divided by one-half the maximum thickness at the weld in inches, whichever is less.

Section III requires heat treatment of P-No. 1 materials in the temperature range of 1100 to 1250°F (600 to 675°C) for 30 min when the thickness is ½ in (12.7 mm) or less, for 1 h/in (1 h/25 mm) of thickness for thickness over ½ to 2 in (12.7 mm to 50 mm), and 2 h plus 15 min for each additional inch of thickness over 2 in (50 mm). In this case the thickness is defined as the lesser of (1) the thickness of the weld, (2) the thinner of the pressure retaining parts being joined, or (3) for structural attachment welds, the thickness of the pressure retaining material.

ASME Section III exempts P-No. 1 materials in piping systems from mandatory heat treatment based on thickness and carbon content. When the materials being joined are 1½ in (38 mm) or less, the following exemptions apply: (1) a carbon content of 0.30 percent or less with a nominal thickness of 1¼ in (32 mm) or less, (2) a carbon content of 0.30 percent or less with a nominal wall thickness of 1½ in (38 mm) when a preheat of 200°F (95°C) is applied, (3) a carbon content over 0.30 percent with a nominal wall thickness of ¾ in (19 mm) or less, and (4) a carbon content over 0.30 percent and a nominal wall of 1½ in (38 mm) or less when a preheat of 200°F (95°C) is applied.

ASME Section III also requires controlled heating and cooling. Above 800°F (430°C) the rate shall not exceed 400°F/h (225°C/h) divided by the maximum thickness in inches but not to exceed 400°F/h (205°C/h). The rate need not be less than 100°F/h (55°C/h). Time and temperature recordings must be made available to the Authorized Nuclear Inspector.

B31.5 requires heat treatment of P-No. 1 material greater than ¾ in (19 mm) in the temperature range of 1100 to 1200°F (600 to 650°C) for 1 h/in (1 h/25 mm) of wall thickness with a 1 h minimum. The governing thickness is the thicker of the abutting edges for butt welds and the throat thickness for fillet socket and seal welds. Controlled heating and cooling rates are specified.

B31.3 has similar requirements except that differing thickness definitions are applied to branch, fillet, and socket welds, and there are no specified heating or cooling rates.

B31.4 and B31.11 both require stress relieving when the wall thickness exceeds 1¼ in (32 mm), or 1½ in (38 mm) if a 200°F (95°C) preheat is applied. No specific temperature is specified. B31.8 on the other hand requires stress relief if the carbon content exceeds 0.32 percent, the carbon equivalent (C + ¼ Mn) exceeds 0.65 percent, or the wall thickness exceeds 1¼ in (32 mm). Carbon steels are to be heat treated at 1100°F (600°C) or higher as stated in the qualified welding procedure.

Requirements for postweld heat treatment of many different ferrous alloy steels are given in the various codes. As in the case of the carbon steels, there are variations in requirements from code to code.

In the case of welding dissimilar metals, the codes most often specify that the heat treatment which invokes the higher temperature requirement be applied to the weld joint. In applying this criteria many factors should be considered. See the section ''Dissimilar Metals'' for some options. Another possibility is to take advantage of longer-time and lower-temperature heat treatments permitted by some codes.

In the end, the best source of information for specific requirements regarding heat treatment is the particular code mandated by law or contract. Where none is invoked, the various codes can be used as guides.

Verification Activities—Inspection, Nondestructive Examination, Testing, and Quality Assurance and Quality Control

Introduction. Activities involved in verifying that fabrication meets the specified quality level may be broadly categorized as inspection, NDE, testing and QA and QC.

The terms *inspection, examination*, and *testing* are still often used interchangeably. The ASME Boiler and Pressure Vessel Codes have begun to establish specific definitions for these terms. The B31 Codes present a mixture of usages, some following the ASME Boiler and Pressure Vessel Code lead, while others are less definitive. The reader is directed to the individual codes to see how these terms are used. In general, the ASME Boiler and Pressure Vessel Code practice will be followed in this section.

Inspection relates to those activities performed by the owner, the owner's agent, or a third party. All other activities are usually performed by fabricator personnel.

The term *examination* is applied to nondestructive methods of examination, while *testing* refers to traditional hydrostatic and pneumatic tests for leakage. QA and QC relate to in-plant or on-site programs, whose function is to control the various activities which affect quality.

Inspection. Inspection, as used in ASME Section I, III and B31.1 for Boiler External Piping, covers those activities which the authorized inspector (AI) or authorized nuclear inspector (ANI) performs in verifying compliance with the applicable code. The AI or ANI is employed by a third party; is independent of the owner, fabricator, or installer; is an employee of a state or municipality in the United States, a Canadian province, or an insurance company authorized to write boiler insurance; and is qualified by written examination as required by state or provincial rules.

In the B31 Piping Codes, inspection is the verification activity performed by the owner or the owner's agent. Specific requirements for qualification of inspectors are outlined in the individual code sections.

The manner in which an inspector verifies compliance is generally left to the discretion of the individual. It may take the form of detailed visual examinations; witnessing of actual operations such as bending, welding, heat treatment, or NDEs; review of records; or combinations thereof. Much relies on the degree of confidence the inspector has in the fabricator's programs and personnel. B31.3 has mandatory sampling requirements for this activity.

Examination

Types of Examinations. When used in the various codes, examination refers to the verification work performed by employees of the fabricator, much of which falls into the category of NDE. NDEs most often referenced by code and applied to the fabrication and installation of piping components and systems are:

Visual
Radiographic
Ultrasonic
Liquid penetrant
Magnetic particle

Eddy current examination is often used to evaluate the quality of straight lengths of pipe as they are manufactured but is not often used in fabrication activities. Although not referenced by most codes, bubble testing, halogen diode probe testing, or helium pass spectrometer leak testing may be invoked by contract when, in the opinion of the designer, they will contribute to the integrity of the system. While these methods are referred to as leak tests, their methodology is outlined in Article 10 of ASME Section V Nondestructive Examination.

Accept-reject criteria and the extent to which the various NDEs are to be applied are in the applicable code.

The following are brief descriptions of NDEs as they apply to piping. For much more detailed information the reader is referred to various publications of the American Society for Nondestructive Testing (ASNT),[36] particularly the Nondestructive Testing Handbooks.

1. *Visual examination:* Visual examination is probably the oldest and most widely used of all examinations. It is used to ascertain alignment of surfaces, dimensions, surface condition, weld profiles, markings, and evidence of leaks, to name a few. In most instances the manner of conducting a visual examination is left to the discretion of the examiner or inspector, but more recently, written procedures outlining such things as access, lighting, angle of vision, use of direct or remote equipment, and checklists defining the observations required are being used. Visual examination takes place throughout the fabrication cycle along with QA and QC checks. At setup, this would consist of verifying materials, weld procedures, welder qualifications, filler metal, and weld alignment, and on completion of fabrication, such things as terminal dimensions, weld profile, surface condition, and cleanliness.

2. *Radiographic examination:* When the need for greater integrity in welding must be demonstrated, the most frequently specified examination is radiography. Since the internal condition of the weld can be evaluated, it is referred to as a *volumetric* examination.

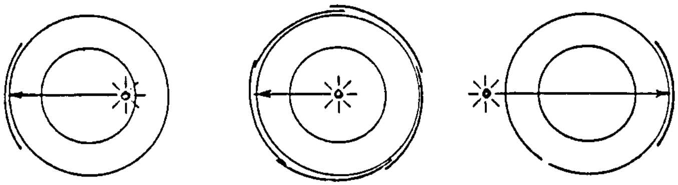
Radiographic sources used for examination of piping are usually X-rays or gamma rays from radioactive isotopes. While X-ray equipment is often used, it has limitations in that it often requires multiple exposures for a single joint, and special equipment, such as linear accelerators, are needed for heavier thicknesses. Although X-ray machines produce films with better clarity, they are not as practical in the field because of space limitations and portability. In the field, radioactive isotopes are used almost exclusively because of their portability and case of access. For wall thicknesses up to about 2½ in (63.5 mm) of steel, the most commonly used isotope is iridium 192. Beyond this cobalt 60 is used for wall thickness up to about 7 in (179 mm).

Radioactive sources normally used in piping work range in intensity from a few curies up to about 100 curies. Each source decays in intensity in accordance with its particular half-life. As the intensity decays, longer exposure times are required. Iridium 192 has a half-life of 75 days, while cobalt 60 has a 5.3-year half-life.

Radioactive sources have finite dimensions and as a result produce a shadow effect on the film. This is referred to as geometric unsharpness, and it is directly proportional to the source size and inversely proportional to the distance between the source and the film. ASME Section V has established limits for geometric unsharpness.

Ideally for pipe, the source is placed inside the pipe and at the center of the weld being examined, with film on the outside surface of the weld, thus permitting one panoramic exposure. Where geometric unsharpness precludes this practice, the source may be placed on the inside on the opposite wall and a portion of the weld is shot. Several exposures will be needed. The source may also be placed outside the pipe and the exposure made through two walls. Again this requires multiple exposures and longer exposure times. See Fig. A6.25.

A radiograph is considered acceptable if the required essential hole or wire size



A
Opposite wall

B
Panoramic

C
Double wall

Given:
1. 30-in dia. X 7-in wall C/S pipe
2. 10 cu CO_{60} X 0.051 dia. source
3. 50 cu CO_{60} X 0.125 dia. source
4. 100 cu CO_{60} X 0.181 dia. source
5. Max. allowable geometric unsharpness $Ug = \frac{Fd}{D} = 0.07$ in (ASME Sect. V Art. 2 para. T-274)
6. Use Kodak "AA" Film with a 2.5 film density

Min. SFD = 5.1 in for 10 cu AX 0.051 in dia.
12.5 in for 50 cu X 0.125 in dia.
18.1 for 100 cu X 0.181 in dia.

Using the parameter established in 1 above as well as 5 and 6, it would be possible to:

(*a*) Use a 10-cu source as established in 2 above and shoot the pipe using the panoramic technique, sketch B above, with an exposure time of 3 hrs or

(*b*) Use a 50-cu source as established in 3 above and shoot the pipe using the panoramic technique, sketch B above, with an exposure time of 1 hour 15 min or

(*c*) Use a 100-cu source as established in 4 above and shoot the pipe using the opposite wall technique, sketch A above, with an exposure time of 50 min. As many as six exposures might be required—total 5 hrs.

FIGURE A6.25 Effect of source size on radiographic technique.

from the image quality indicator is visible on the film. See ASME Section V for information on this subject.

3. *Ultrasonic examination:* Ultrasonic examination is used in piping for the detection of defects in welds and materials as well as for determining material thickness. A short burst of acoustic energy is transmitted into the piece being examined and echoes reflect from the various boundaries. An analysis of the time and amplitude of the echo provides the examination results.

A clock in the equipment acts to initiate and synchronize the other elements. It actuates a pulsar to send a short-duration electrical signal to a transducer, usually at a frequency of 2.5 MHz. The transducer converts the electrical signal to mechanical vibration. The vibration as ultrasound passes through a couplant (such as glycerine) and through the part at a velocity which is a function of the material. As the sound reflects from various boundaries, it returns to the initiating transducer or sometimes to a second one where it is converted back to an electrical signal which is passed to a receiver amplifier for display on a cathode-ray tube. The horizontal axis of the display relates to time and the vertical axis relates to amplitude. The indication on the extreme left will show the time and amplitude of the signal transmitted from the transducer. Indications to the right will show the time and degree of reflection from various boundaries or internal discontinuities.

The ability of an ultrasonic examination to detect discontinuities depends a great deal on the part geometry and defect orientation. If the plane of the defect is normal to the sound beam, it will act as a reflecting surface. If it is parallel to the sound beam, it may not present a reflecting surface and accordingly may not show on the oscilloscope. Therefore, the search technique must be carefully chosen to assure that it will cover all possible defect orientations.

The most serious defect in a pipe butt weld is that which is oriented in the radial direction. The most commonly used technique for detecting such defects is the shear wave search. In this procedure, the transducer is located to one side of the weld at an angle to the pipe surface. The angle is maintained by a lucite block which transmits the sound from the transducer into the pipe. The sound will travel at an angle through the pipe and weld. Being at an angle, it will reflect from the pipe surfaces until it is attenuated. Any surface which is normal to the beam, however, will reflect a portion of the sound back to the transducer and show as an indication on the oscilloscope. See Fig. A6.26. If the beam angle and the material thickness are known, the reflecting surface can be located and evaluated.

Prior to and periodically during each search, the equipment is calibrated against artificial defects of known size and orientation in a calibration block. The block must be representative of the material being searched (i.e., an acoustically similar material, with appropriate thickness, outside contour, surface finish, and heat-treated condition).

A variation of ultrasonic examination can be used to measure material thickness. If the speed of sound within the material is known, the time it takes for the signal to traverse the thickness and return can be converted to a thickness measurement.

4. *Liquid penetrant examination:* Penetrant-type examinations are suitable for surface examinations only but are very sensitive. They require a fairly smooth surface, since surface irregularities such as grinding mark indications can be confused with defect indications. The surface to be examined is thoroughly cleaned with a solvent and then coated with a penetrating-type fluid. Sufficient time is allowed to permit the fluid to penetrate into surface discontinuities. The excess penetrant is removed by wiping with cloths until all evidence of the penetrant is removed. A developer which acts somewhat like a blotter is then applied to the surface. This

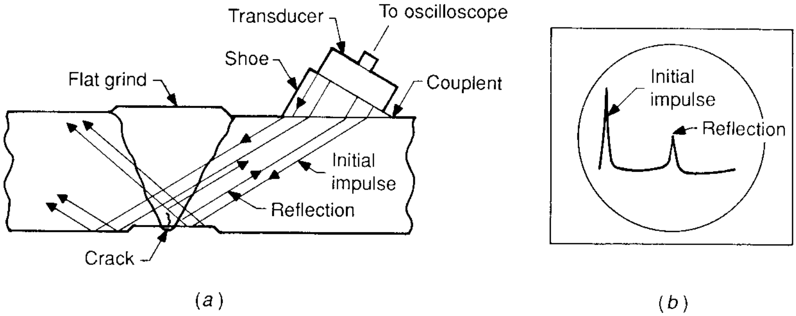


FIGURE A6.26 Ultrasonic shear wave search. (*a*) Search arrangement; (*b*) oscilloscope.

draws the penetrant out of the discontinuity, and it will appear on the surface as an indication. Obviously, the success of the examination depends on the visibility of the indication. To enhance this, the penetrant contains colored dyes which can be seen under normal light, or fluorescent dyes which are viewed under ultraviolet light. The most common case is a red dye penetrant with a white developer.

5. *Magnetic particle examination:* Magnetic particle examination is essentially a surface-type examination, although some imperfections just below the surface are detectable. This type of examination is limited to materials which can be magnetized (paramagnetic materials), since it relies on the lines of force within a magnetic field.

The item to be examined is subjected to a current which will produce magnetic lines of force within the item. The surface is then sprayed with a fine iron powder. The powder will align itself with the lines of force. Any discontinuity normal to the lines of force will produce a leakage field around it and a consequent buildup of powder which will pinpoint the defect. The examination must be repeated at 90° to detect discontinuities which were parallel to the original field.

There are a great many variations of magnetic particle examination depending on the manner in which the field is applied and whether the particles are wet or dry and fluorescent or colored.

Methodology. The ASME Boiler and Pressure Vessel, B31.1 and B31.3, require certain NDEs to be performed in accordance with the methods described in ASME Section V Nondestructive Examination. The pipeline codes, B31.4, B31.8, and B31.11, refer to API-1104 for Radiographic Procedures. In some cases, particularly in visual examination, requirements are given but no specific methodology is stated. In others, alternative parameters or qualification requirements are given. The specific requirements of the individual codes should be consulted.

Qualification Requirements. Qualification of procedures and personnel used in NDEs are required by most codes. When ASME Section V or API-1104 are invoked by the referencing code, a written procedure is required and it must be demonstrated to the satisfaction of the AI, ANI, owner, or owner's agent, whichever is applicable. Similarly personnel who perform NDEs must be trained, qualified, and certified. The most frequently invoked qualification document is SNT-TC-1A[37]; it is also accepted by B31.1 for qualification of personnel performing visual examinations. Some codes permit alternatives, such as AWS-QC-1.[38]

TABLE A6.9 Acceptance Standards for Visual Examination

The following indications are unacceptable:

1. Crack(s) on external surfaces
2. Undercut on surface greater than 1⁄32 in (1.0 mm) deep
3. Weld reinforcement greater than specified in ASME Table 127.4.2
4. Lack of fusion on surface
5. Incomplete penetration (applies only when inside surface is readily accessible)
6. Any other linear indications greater than 3⁄16 in (5.0 mm) long
7. Surface porosity with rounded indications having dimensions greater than 3⁄16 in (5.0 mm) or 4 or more rounded indications separated by 1⁄16 in (2.0 mm) or less edge to edge in any direction. Rounded indications are indications which are circular or elliptical with their length less than 3 times their width

Source: From ASME B31.1 1995 ed.

Extent of Examination. The applicable code will define the extent of examination required for piping systems under its coverage. The degree of examination and the examination method and alternatives are a function of the degree of hazard which might be expected to occur in the event of failure. Pressure, temperature, toxicity of the fluid, and release of radioactive substances are some of the considerations. Added layers of examinations may be required as the perceived hazard increases.

Accept-Reject Criteria. The applicable code will also define the items to be examined and the accept-reject criteria to be applied. Table A6.9 shows the acceptance standards applicable to the visual examination of butt welds under B31.1. Other piping codes have similar but not necessarily identical criteria.

Table A6.10 shows acceptance standards for radiographic examination. Indications interpreted as cracks, incomplete penetration, or lack of fusion are not permitted. Porosity and elongated indications are kept within certain limits. The acceptance standards for ultrasonic examination are similar.

TABLE A6.10 Acceptance Standards for Radiography

Welds that are shown by radiography to have any of the following types of discontinuities are unacceptable:

1. Any type of crack or zone of incomplete fusion or penetration
2. Any other elongated indication with a length greater than
   a. 1⁄4 in (6.0 mm) for t up to 3⁄4 in (19.0 mm)
   b. 1⁄3 t for t from 3⁄4 in (6.0 mm) to 2 1⁄4 in (57.0 mm) inclusive
   c. 3⁄4 in (19.0 mm) for t over 2 1⁄4 in (57.0 mm) where t is the thickness of the thinner portion of the weld
3. Any group of indications in a line that have an aggregate length greater than t in a length of 12 t, except where the distance between successive indications exceeds 6L where L is the longest indication in the group
4. Porosity in excess of that shown as acceptable in Appendix A-250 of Section I of the Boiler and Pressure Vessel Code
5. Root concavity when there is an abrupt change in density indicated on the radiograph

Note: t pertains to the thickness of the weld being examined. If a weld joins two members having different thicknesses at the weld, t is the thinner of these thicknesses.

Source: ASME B31.1 1995 ed.

TABLE A6.11 Acceptance Standards for Magnetic Particle and Liquid Penetrant Examinations

The following relevant indications are unacceptable:
1. Any cracks or linear indications
2. Rounded indications with dimensions greater than 3⁄16 in (5.0 mm)
3. Four or more rounded indications in a line separated by 1⁄16 in (2.0 mm) or less edge to edge
4. Ten or more rounded indications in any 6 in^2 (3870 mm^2) of surface with the major dimension of this surface not to exceed 6 in (150 mm) with the area taken in the most unfavorable location relative to the indications being evaluated

Source: From ASME B31.1 1995 ed.

Both magnetic particle and liquid penetrant examinations have identical limits. See Table A6.11

Other types of NDEs, such as acoustic emission, bubble testing, and mass spectrometer testing, are not required by the various codes. They can be invoked by contract and the acceptance standards must be a matter of agreement between the contracting parties.

Testing. All of the piping codes outline some type of pressure test to determine leak tightness. Since the completed piping system is usually subjected to some type of test in the field after installation, shop testing of subassemblies is infrequent. In those cases where the assembly cannot be field tested, where welds in the assembly will not be exposed for examination during the field test, and in other special situations, shop testing may be required. Shop testing must meet all of the requirements for field testing. See the section ‘‘Installation’’ for particulars.

Quality Assurance and Quality Control. ASME Section III has very specific requirements for QA programs. ASME Section I has requirements for QC programs. The B31 Piping Codes do not require any formal written program at this time. Refer to these codes for detailed information on this subject.

Cleaning and Packaging. Cleanliness of piping subassemblies is a matter of agreement between the fabricator and purchaser. As a minimum the fabricator will clean the inside of the subassembly of loose scale, weld spatter, machining chips, etc., usually with jets of compressed air. For those systems which require a greater degree of cleanliness several options are available. For specific information refer to PFI Standard ES-5 ‘‘Cleaning of Fabricated Pipe.’’[39] See also the following specifications published by the Steel Structures Painting Council:[40]

SSPC—SP 2 Hand Tool Cleaning

SSPC—SP 3 Power Tool Cleaning

SSPC—SP 6 Commercial Blast Cleaning

SSPC—SP 8 Pickling

SSPC—SP 10 Near-white Blast Cleaning

For ferritic steels the inside surfaces may be cleaned by turbinizing to remove loosely adhering mill scale and heavy rust. Wire brushing and grinding may also be employed for removal of more tightly adhering scale, rust, etc.; however, the most effective method for removal of tight scale is blasting with sand, shot, or grit.

For guidance on blasting methods and degrees of cleanliness refer to PFI Standard ES-29 ‘‘Abrasive Blast Cleaning of Ferritic Piping Materials.’’[41]

Pickling is an equally effective method of cleaning. It is most often used for cleaning large quantities of straight tubes prior to fabrication or small-size (about NPS 4) subassemblies where blasting is not as effective. Its application is limited by the availability and size of pickling tanks. A hot solution of sulfuric acid (H_2SO_4) is most commonly used, although cold hydrochloric acid (HCl) is also recommended. See SSPC—SP 8 ‘‘Pickling.’’

For the 9Cr-1Mo-V materials, aluminum-oxide or silicon-carbide grit, sand or vapor blasting is preferred. Steel shot or grit which has been previously used to clean iron-bearing materials should be avoided. Acid pickling should also be avoided since damaging hydrogen embrittlement may occur.

Austenitic stainless steels normally do not require cleaning except for a degreasing with solvent-saturated cloths to remove traces of greases or cutting oils. Subassemblies which have been heated for bending or which have been given a carbide solution heat treatment will have a tightly adhering chromic oxide scale. Pickling and passivating in a solution of hydrofluoric and nitric acid will remove the scale and passivate the exposed surface. Here again, the equipment for pickling may limit the size of the subassembly. See ASTM A 380 published by the American Society for Testing Materials.[42] Blasting may also be used, but new silica sand or aluminum-oxide grit is required. Sand or grit previously used on ferritic pipe will contaminate the pipe surface with iron particles, and it will subsequently rust. The blasted surface should be treated with a solution of nitric acid to passivate the surface.

For extreme cleanliness, steam degreasing and rinsing with demineralized water may be employed.

The external surfaces of pipe may be left as is, painted, or otherwise preserved. See PFI Standard ES-34 ‘‘Painting of Fabricated Piping.’’[43]

Depending on the need for maintaining rust-free interior surfaces, the pipe inside diameter may be coated with different preservatives, or desiccants may be employed during shipping and storage.

For shipping, the ends of subassemblies are equipped with some type of end protection to preclude damage to weld end bevels or flange faces during shipment and field handling. See PFI Standard ES-31 ‘‘Standard for Protection of Ends of Fabricated Piping Assemblies.’’[44]

During shop operations, it is common practice to move piping assemblies with overhead or floor cranes, usually with chain or wire rope slings. For austenitic stainless steels and nonferrous materials which could be damaged or contaminated, use of nylon slings is recommended.

INSTALLATION

Drawings

Drawings used for piping system installation may vary greatly. Often orthographic projections of the building showing several systems or single systems, depending on complexity, are used. In many cases single or multiple isometric drawings of a single system are used. These of course are not to scale but are convenient for planning, progress recording, or record keeping when required by quality programs. In all cases where prefabricated subassemblies are being erected, these drawings will have been marked up to show the locations and mark numbers of the individual subassemblies, the location and designations of field welds, and the locations and markings of hangers.

Erection Planning

Planning is vitally important in installing a piping system. Many factors must be considered, among them accessibility to the building location, coordination with other work, availability and accessibility of suitable welding and heat treatment equipment, availability and qualification of welders and welding procedures, rigging, scaffolding, and availability of terminal equipment.

Each of the system components should also be carefully checked to assure correctness. Valves and other specialty items in particular should be checked to assure they are marked with flow arrows, that the handwheels or motor operators are properly oriented, and that the material to be welded is compatible with the material of the piping. Special valves for use in carbon steel systems are sometimes furnished as 5 percent chrome material, and thermowells are often not of the same chemical composition as the pipe. This may not be apparent from the drawings. Such a preliminary check will indicate the need for alternate welding procedures and preclude problems later.

The location of the work and accessibility to it should be viewed. It may not be possible to install an overly long subassembly after other equipment or building structure is in place. A common practice in the power field is to have large, heavy assemblies often found in the main steam and reheat lines of large central stations erected with the structure. In other cases, a preliminary review may show interferences from an existing structure, cable trays, ducts, or other piping which are not apparent from the drawings. The locations of the terminal points on equipment should be checked to assure that they are correct. The type, size, rating, or weld preparation of the connection should be checked to assure that it will match the piping. Solutions to any problems can be devised with the designer before work starts.

The ideal way to begin erection is to start at some major piece of equipment or at a header with multiple outlets. Install the permanent hangers if possible. If these are to be welded to the structure, some prudence should be exercised, since the final location of the line may warrant some small relocation to assure that the hanger is properly oriented relative to the piping in its final position. Obviously a certain number of temporary supports will be needed. Welding of temporary supports to the building structure or to the piping itself should be avoided or used only with the approval of the responsible engineers. Variable spring and constant-support-type hangers should normally be installed with locking pins in place, assuring that they function as a rigid support during the erection cycle. Where welded attachments to the pipe are involved, it is preferred that they be installed in the shop as part of the subassembly.

If possible, the major components of the system should be erected in their approximate final position prior to the start of any welding. This will reveal any unusually large discrepancies which may result from equipment mislocation, fabrication error, or tolerance accumulations. Adjustments or corrections can then be decided upon. Long, multiplane systems can absorb considerable tolerance accumulation without the need to modify any part. Short, rigid systems may not be able to accommodate any tolerance accumulation, and it may be necessary to rework one or more parts.

Cold Spring

Both the B31.1 and B31.3 Codes address cold springing in detail. Cold spring is the intentional stressing and elastic deformation of the piping system during the erection cycle to permit the system to attain more favorable reactions and stresses in the operating condition.

The usual procedure is to fabricate the system dimensions short by an amount equal to some percentage of the calculated expansion value in each direction. The system is then erected with a gap at some final closure weld, equal to the ‘‘cut shorts’’ in each direction. Forces and moments are then applied to both ends as necessary to bring the final joint into alignment. Once this is done, it is usually necessary to provide anchors on both sides of the joint to preserve alignment during welding, postweld heat treatment, and final examination. When the weld is completed and the restraining forces are removed, the resulting reactions are absorbed by the terminal points, and the line is in a state of stress. During start-up the line expands as the temperature increases, and the levels of stress and terminal reactions resulting from the initial cold spring will decrease. For the 100 percent cold sprung condition, the reactions and stress will be maximum in the cold condition and theoretically zero in the hot condition. It should be borne in mind that it is very difficult to assure that a perfect cold spring has been attained and for this reason the codes do not permit full credit in the flexibility calculations. Also remember that lines operating in the creep range will ultimately attain the fully relaxed condition. Cold spring merely helps it get there faster. Cold spring was historically applied to high-temperature systems such as main steam and hot reheat lines in central power stations, but this practice is not as prevalent anymore.

For those involved with the repair of lines which have been cold sprung, or which have achieved some degree of creep, caution should be exercised when cutting into such lines since the line will be in a state of stress when cold. The line should be anchored on either side of the proposed cut to prevent a possible accident.

Joint Alignment

In aligning weld joints for field welding it may be necessary to compromise between a perfect weld fit-up and the location of the opposite (downstream) end of the assembly. The weld bevel may not be perfectly square with the longitudinal axis of the assembly. Even a $\frac{1}{32}$-in (0.8 mm) deviation across the face of the weld bevel can result in an unacceptable deviation from the required downstream location if the joint is aligned as perfectly as possible. Often such a small gap can be tolerated in the welding. If, in order to maintain the downstream location, the gap at the joint is excessive, the joint should be disassembled, and the land filed or ground as needed to attain the required alignment of the weld joint while still maintaining the required downstream position. Flanged connections should be made up hand-tight so that advantage can be taken of the bolt-hole clearances to translate or rotate the assembly for better alignment of downstream connections.

Weld shrinkage of field welds may or may not be important in field assembly. In long flexible systems, they may be ignored. For more closely coupled systems, particularly those using GTAW root-pass welding, this factor should be considered. The degree of longitudinal shrinkage across a weld varies with welding process, heat input, thickness, and weld joint detail. See the section ‘‘Layout, Assembly, and Preparation for Welding.’’ In extreme cases closure pieces may be used. Here, the system is completed except for the final piece. A dummy assembly is then fabricated in place and the closure assembly is fabricated to match the dimensions of the dummy assembly with weld shrinkage of the final welds taken into account.

Cutting, Bending, Welding, Heat Treatment, and Examination

Cutting, bending, and welding operations in the field parallel those used in the shop. See the section ‘‘Fabrication.’’

Mechanical and oxyfuel gas cutting are most commonly used in the field. Plasma cutting may occasionally be used.

Bending, if used at all, is limited to small-diameter piping using relatively simple bending equipment at ambient temperatures. Occasionally in order to correct for misalignment, larger-diameter ferritic piping is bent at temperatures below the lower critical. Please note that this procedure is limited to ferritic materials. Any application of heat to austenitic materials will result in sensitization and loss of corrosion properties. See the section ‘‘Bending.’’ For smaller pipe sizes, torches may be used to supply heat, but for larger, heavier-wall materials and where better temperature control is warranted, heat may be applied by induction or resistance heating units in the same manner as local stress relieving. See the section ‘‘Local Heat Treatment.’’ The heating units are applied to the section of the pipe to be bent. The section of the line upstream of the area to be bent should be anchored to preclude translation or rotation of the installed portion of the line. The anchor should preferably be not more than one or two pipe diameters from the area to be heated. Once the bend area has attained the required temperature, a bending force can be applied on the downstream leg of the pipe until the required bend arc has been obtained. Since most ferritic materials still have reasonably high yield strengths even at lower critical temperatures, care should be exercised. Large bending forces may damage the building structure or crack the line being bent. Apply a reasonable force for the conditions and allow the imposed stress in the bend arc to be relieved by the heat. Then repeat. Progress in this fashion until the required bend is accomplished. Some small amount of overbending may be required to offset the deflection which will occur in the unheated section of pipe between the heated arc and the pulling device. When the bend is completed and allowed to cool, all restraints may then be removed. Little if any force should be needed to align the downstream joint; otherwise additional bending may be needed to further correct the situation. No further heat treatment of the bend arc is needed since the temperatures applied in this bending method are below the lower critical temperature. Corrections to lines with large section modulus or where the required bend arc is large should preferably be made in a shop since better controls can be exercised.

Field welding is more often than not in a fixed position. Welders should be qualified in the 6G position since this qualifies for all positions.

Welding will be done using SMAW, GMAW, FCAW, and GTAW. Some welding processes can be automated using orbital welding techniques. Such practice can result in fewer repairs, provided the bevels and alignment are within tolerance and the welding parameters are carefully selected.

Field postweld heat treatment also follows the practices outlined in the section ‘‘Heat Treatment’’ for local stress-relieving of ferritic materials. This usually involves induction or resistance heating units with recording devices. For small pipe welds, torch heating using temperature-sensitive crayons to control temperature is sometimes used. Exothermic heating to stress-relieve welds is still used on occasion for outdoor applications where heating rates are not required to be controlled.

Exothermic materials are preformed to pipe contour and sized to reflect the wall thickness and desired stress-relieving temperature. They are placed around the weld and ignited, attaining temperature in 5 or 10 min. The actual maximum temperature attained may vary.

NDE in the field will follow the practices outlined in the section ''Verification Activities.'' Radiography is usually limited to radioactive isotopes, although occasionally X-ray equipment may find a use. Most surface examination is conducted using liquid-penetrant methods, since magnetic particle equipment is not as convenient in the field. Ultrasonics are used for thickness verification and in certain situations as an alternative to radiography of welds when permitted by the governing code.

Mechanical Joints

Threaded joints probably represent the oldest method of joining piping systems. The dimensional standards for taper pipe threads are given in ASME B1.20.1.[45] This document gives all required dimensions including number of threads per inch, pitch diameter, and normal engagement lengths for all pipe diameters. Thread cutting should be regarded as a precise machining operation. A typical threading die is shown on Fig. A6.27. For steel pipe the lip angle should be about 25°, but for brass it should be much smaller. Improper lip angle results in rough or torn threads. Since pipe threads are not perfect, joint compounds are used to provide leak tightness. The compounds selected, of course, should be compatible with the fluid carried and should be evaluated for possible detrimental effects on system components. Manufacturers' recommendations should be followed.

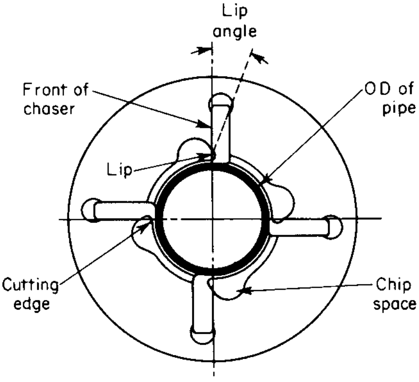


FIGURE A6.27 Threading die.

Where the presence of a joint compound is undesirable, dryseal pipe threads in accordance with ASME B1.20.3[46] may be employed. These are primarily found in hydraulic and pneumatic control lines and instruments.

Flanged joints are most often used where disassembly for maintenance is desired. A great deal of information regarding the selection of flange types, flange tolerances, facings and gasketing, and bolting is found in B16.5. The limitations regarding cast-iron-to-steel flanges, as well as gasket and bolting selection, should be carefully observed. The governing code will usually have further requirements.

Gasket surfaces should be carefully cleaned and inspected prior to making up the joint. Damaged or pitted surfaces may leak. Appropriate gaskets and bolting must be used. The flange contact surfaces should be aligned perfectly parallel to each other. Attempting to correct any angular deviation perpendicular to the flange faces while making up the joint may result in overstressing a portion of the bolts and subsequent leakage. The proper gasket should be inserted making sure that it is centered properly on the contact surfaces. Bolts should be tightened hand-tight. If necessary for alignment elsewhere, advantage may be taken of the bolt hole tolerances to translate or rotate in the plane of the flanges. In no case should rotation perpendicular to the flange faces be attempted. When the assembly is in its final location, bolts should be made up wrench-tight in a staggered sequence. The bolt loading should exert a compressive force of about twice that generated by the internal pressure to compensate not only for internal pressure but for any bending loads which may be imposed on the flange pair during operation. For a greater guarantee against leakage, torque wrenches may be employed to load each bolt or stud to some predetermined value. Care should be exercised to preclude loading beyond the yield point of the bolting. In other cases, special studs that have had the ends ground to permit micrometer measurement of stud elongation may be used. Flange pairs which are to be insulated should be carefully selected since the effective length of the stud or bolt will expand to a greater degree than the flange thicknesses, and leakage will occur. Thread lubricants should be used, particularly in high-temperature service to permit easier assembly and disassembly for maintenance.

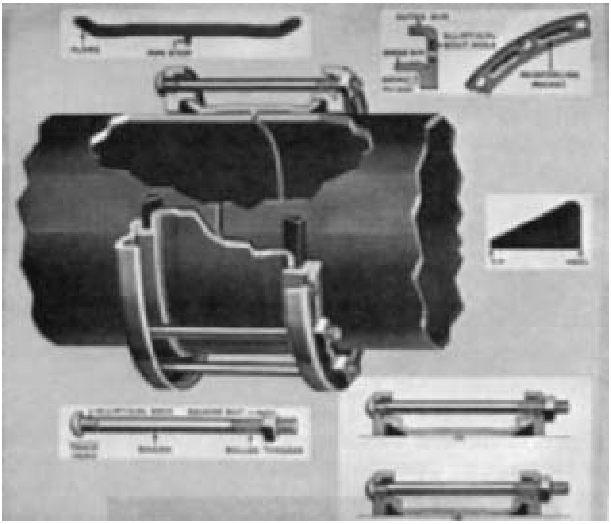


FIGURE A6.28 Compression sleeve (Dresser) coupling for plain-end cast-iron or steel pipe.

There are a great variety of mechanical joints used primarily for buried cast-iron pipelines carrying water or low-pressure gas. They are primarily of the bell and spigot type with variations involving the use of bolted glands, screw-type glands, and various types of gasketing. The reader is referred to AWWA Standards C 111,[47] C 150,[48] and C 600,[49] and to catalogs for proprietary types. For reinforced concrete pipe, AWWA Standards C 300,[50] C 301,[51] and C 302,[52] should be consulted. Compression-sleeve couplings such as the Dresser coupling (see Fig. A6.28) and the Victualic coupling (see Fig. A6.29) are widely used for above- and below-ground services, both with cast-iron and steel pipe. Consult the manufacturers' catalogs for more information. Refer to Chap. A9 of this handbook.

Tubing

Copper, aluminum, steel, and stainless-steel tubing are frequently used in hydraulic, pneumatic, and sampling systems. Installation is most often concerned with protection of such materials from damage, since they are often associated with control systems. The manner of protection is left to the designer's judgment.

Lighter wall tubing is often bent using small compression-type benders. Tubing is joined to itself and to pipe-size fitting and components with a variety of proprietary tubing fittings which are described in Chap. A2. Some heavier-wall stainless-steel tubing is welded using specially designed socket welding fittings. GTAW welding with filler metal added is used for such applications.

FIGURE A6.29 Victualic coupling for grooved-end cast-iron or steel pipe.

Pipe Supports

This section offers some thoughts on the installation of piping supports. The design, manufacture, and influence of supports on the system flexibility are outlined in Chaps. B4 and B5 of this book.

As pointed out earlier, economics and efficiency dictate that it is preferable to install the permanent supports for a system as the first step, thus minimizing the need for temporary supports. In so doing considerable judgment should be exercised, since there can be minor variations between the as-designed and as-installed line location. Resilient and constant-effort support should be locked with stops to preclude change in supporting effort as the line is being installed. Only after the line has been completely welded, tested, and insulated should the stops be removed. Once removed, the resilient and constant-effort supports should be carefully adjusted to their ''cold'' positions. This may take several iterations, since adjustment of any one will change the loading on the adjacent ones. Systems with multiple constant-effort supports can be especially troublesome. Since the support design is most often based on theoretical values of weight of the pipe, insulation, and the fluid, there will be some difference between the actual and calculated supporting effort. Where rigid supports are involved, this variation will be taken up automatically. Where a system is designed with multiple resilient or constant-effort supports, every effort should be made to incorporate one or more rigid supports in the design to absorb the variation between actual and theoretical loads. Otherwise it may be necessary, with the approval of the designer, to modify the spring load-carrying settings.

As the line goes to operating temperature, it should be carefully observed to assure that there are no unforeseen interferences with its required expansion, particularly at nearby structures, floor sleeves, or adjacent lines or by restrained branch connections. Some modification may be required to assure free expansion of the line. All resilient supports and constant-effort supports should be checked during initial start-up to assure that they are functioning properly, and after the line has been at operating temperature for several hours, they should be checked to verify that they are in the required "hot" operating condition. It may be necessary to readjust some units to match the calculated "hot" loading. These settings should be checked on a regular basis for the first few weeks of service, particularly in systems operating in the creep range, since the temperature will begin to relieve locked-in construction stresses, and the line may choose a different, more relaxed location. Readjustments may be required. If after some time in service, the resilient and constant-effort supports still require significant adjustment (i.e., the system cannot be balanced), a complete review of the flexibility analysis, expansion calculations, weight calculations, hanger, design, and installation procedures should be made to determine the cause. Resilient and constant-effort support units which are not functioning in the spring range (i.e., they have become "solid" or "loose") may impose undesirably high stresses in the line if they are not corrected, which can lead to premature failure or significantly reduced system life.

Leak Testing

At one time, complex shapes were pressure-tested to determine their suitability for the service intended. This involved stressing the component to a point above service stresses, but below bursting stress, and was referred to as a pressure test. Currently most codes require some type of test to determine leak tightness rather than service suitability.

The most common method of leak testing for piping systems is the hydrostatic test. Usually this involves water at ambient temperature as the test medium. B31.1 requires that the system be pressurized to 1.5 times the design pressure, ASME III, to 1.25 times the design pressure, and B31.3 requires a test pressure of 1.5 times the design pressure adjusted by the ratio of the allowable stress at test temperature divided by the allowable stress at operating temperature. In each case, however, the test pressure of unisolated equipment or some function of the yield stress of the line material may be a limiting factor. See the applicable code for particulars. The line must be held at test pressure for at least 10 min, but may be reduced as permitted in the applicable code until the examination for leakage is complete.

Depending on the specific situation, alternative test fluids may be employed. As an example, in a liquid sodium system, where water could be very hazardous, or in cases where the possibility of freezing exists, a hydrocarbon or other fluid might be used.

In instances where water or other liquids are unacceptable, or where supports may not be adequate to carry the added weight of water, pneumatic tests may be performed. Pneumatic tests are potentially more dangerous than hydrostatic tests, and extreme care should be exercised. B31.1 and ASME III require the pneumatic test be performed at not less than 1.2 times the design pressure, while B31.3 limits the test to 1.1 times design. In each case, the limits regarding equipment and yield strength previously cited for hydrostatic tests also apply.

Prior to the test a detailed review of the section of the line to be tested should be made with the following in mind:

1. Temporary supports for those sections where the permanent supports were not designed to take the additional weight of the test fluid.
2. Isolation or restraints on expansion joints.
3. Isolation of equipment or valves which may be overstressed at test pressure.

4. Location of test pump and the need for additional test gauges if there is a significant head variation due to elevation differential.

5. Location of vents and drains.

6. Location of a relief valve to preclude excessive overpressure due to possible thermal expansion of the test fluid.

7. Consideration of the probable ambient test temperature relative to the expected brittle fracture toughness of the system materials. Heating the water may be a solution.

8. Alternative test fluid.

9. Accessibility to the weld joints for inspection. Some codes require that the weld joints be left exposed until after the test.

10. Assurance that no part of the system will exceed 90 percent of its yield strength.

It is advisable to prepare a written procedure outlining the scope and boundaries of each test to assure that it is performed in a safe manner. The codes vary a bit on the required test pressures, time at test pressure, pressure during inspection for leakage, and whether alternative tests may be performed. It is advisable to look at each one specifically. For more details, refer to Chap. B14 of this handbook.

REFERENCES

1. ASME 31.1, ‘‘Power Piping Code,’’ American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017.
2. ASME Section I, ‘‘Power Boiler Code,’’ ASME.
3. ASME Section III, ‘‘Nuclear Power Plant Components,’’ ASME.
4. ASME Section V, ‘‘Nondestructive Examination,’’ ASME.
5. ASME Section IX, ‘‘Welding and Brazing Qualifications,’’ ASME.
6. ASME B36.10M, ‘‘Welded and Seamless Wrought Steel Pipe,’’ ASME.
7. ASME B16.5, ‘‘Pipe Flanges and Flanged Fittings,’’ ASME.
8. Manufacturers Standardization Society of the Valve and Fitting Industry, Inc., 127 Park Street, N.E., Vienna, VA 22180.
9. American Petroleum Institute, 1220 L Street, N.W., Washington, DC 20005.
10. Pipe Fabrication Institute, P.O. Box 173, Springdale, PA 15144.
11. American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.
12. ASME B16.34, ‘‘Valves—Flanged, Threaded and Welding End,’’ ASME.
13. ASME B16.9, ‘‘Wrought Steel Butt Welding Fittings,’’ ASME.
14. ASME B16.1, ‘‘Cast-Iron Pipe Flanges and Flanged Fittings,’’ ASME.
15. PFI ES-3, ‘‘Fabricating Tolerances,’’ PFI.
16. *Welding Handbook,* Seventh ed., American Welding Society, 550 N.W. LeJeune Road, Miami, Fl 33126.
17. Harvey, John F., *Theory and Design of Modern Pressure Vessels,* Second ed., p 47, Van Nostrand Reinhold Company, New York, NY 10001.
18. ASME B31.3, ‘‘Process Piping,’’ ASME.
19. PFI ES-24, ‘‘Pipe Bending Methods, Tolerances, Process and Material Requirements,’’ PFI.

20. *The Metals Handbook,* American Society for Metals, Metals Park, OH 44073.
21. Copper Development Assn., Inc., Greenwich Office Park 2, P.O. Box 1840, Greenwich, CT 06836.
22. Huntington Alloys, Inc., Guyan River Road, P.O. Box 1958, Huntington, WV 25720.
23. ASME B31.4, "Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols," ASME.
24. ASME B31.8, "Gas Transmission and Distribution Piping Systems," ASME.
25. ASME B31.11, "Slurry Transportation Piping Systems," ASME.
26. API 1104, "Standard for Welding Pipe Lines and Related Facilities," American Petroleum Institute.
27. ASME B31.5, "Refrigeration Piping," ASME.
28. AWS D10.9, "Qualification of Welding Procedures and Welders for Pipe and Tubing, Specification for," AWS.
29. ASME Section II, Part C, "Welding Rods, Electrodes and Filler Metals," ASME.
30. PFI ES-21, "Internal Machining and Fit-up of GTAW Root Pass Circumferential Butt Welds," PFI.
31. PFI ES-7, "Minimum Length and Spacing for Welded Nozzles," PFI.
32. PFI ES-1, "Internal Machining and Solid Machined Backing Rings for Circumferential Butt Welds," PFI.
33. Sosnin, H. A., *The Theory and Technique of Soldering and Brazing of Piping Systems,* NIBCO INC. Elkhart, IN 46514.
34. Linnert, George E., *Welding Metallurgy,* Third ed., Vol. 2, American Welding Society.
35. United States Steel, *The Making, Shaping and Treating of Steel,* Tenth ed., Association of Iron and Steel Engineers, Suite 2350, Three Gateway Center, Pittsburgh, PA 15222.
36. American Society for Nondestructive Testing, 1711 Harlingate Lanes, P.O. Box 28518, Columbus, OH 43228-0518.
37. SNT-TC-1A, "Personnel Qualification and Certification in Nondestructive Testing," ASNT.
38. AWS QC-1, "Standards and Guide for Qualification and Certification of Welding Inspectors," AWS.
39. PFI ES-5, "Cleaning of Fabricated Pipe," PFI.
40. Steel Structures Painting Council, 4400 Fifth Ave., Pittsburgh, PA 15213.
41. PFI ES-29, "Internal Abrasive Blast Cleaning of Ferritic Piping Materials," PFI.
42. ASTM A-380, "Standard Practice for Cleaning and Descaling Stainless Steel Parts, Equipment and Systems," American Society for Testing Materials, 1916 Race St. Philadelphia, PA 19103-1187.
43. PFI ES-34, "Painting of Fabricated Pipe," PFI.
44. PFI ES-31, "Standard for Protection of Ends of Fabricated Piping Assemblies," PFI.
45. ASME B1.20.1, "Pipe Threads, General Purpose (inch)," ASME.
46. ASME B1.20.3, "Dryseal Pipe Threads," ASME.
47. C-111/A21.11, "Rubber Gasketed Joint for C.I. Pipe and Fittings," American Water Works Association, 6666 W. Quincy Ave., Denver, CO 80235.
48. C-150/A21.50, "Thickness Design of Ductile Iron Pipe," AWWA.
49. C-600, "Installation of C.I. Water Mains," AWWA.

50. C-300, ‘‘Reinforced Concrete Water Pipe—Steel Cylinder Type—Not Prestressed,’’ AWWA.
51. C-301, ‘‘Reinforced Concrete Water Pipe—Steel Cylinder Type—Prestressed,’’ AWWA.
52. C-302, ‘‘Reinforced Concrete Water Pipe—Non-Cylinder Type—Not Prestressed,’’ AWWA.