

Chapter 4

PE Pipe and Fittings Manufacturing

Introduction

The essential steps of PE pipe and fitting production are to heat, melt, mix and convey the raw material into a particular shape and hold that shape during the cooling process. This is necessary to produce solid wall and profile wall pipe as well as compression and injection molded fittings.

All diameters of solid wall PE pipe are continuously extruded through an annular die. Whereas, for large diameter profile wall pipes, the profile is spirally wound onto a mandrel and heat-fusion sealed along the seams.

Solid wall PE pipe is currently produced in sizes ranging from 1/2 inch to 63 inches in diameter. Spirally wound profile pipe may be made up to 10 feet in diameter or more. PE pipe, both the solid wall type and the profile wall type, are produced in accordance with the requirements of a variety of industry standards and specifications such as ASTM and AWWA. Likewise, the PE fittings that are used with solid wall PE pipe are also produced in accordance with applicable ASTM standards. Refer to Chapter 5 for a list of the commonly used PE pipe standards.

Generally, thermoplastic fittings are injection or compression molded, fabricated using sections of pipe, or machined from molded plates. Injection molding is used to produce fittings up through 12 inches in diameter, and fittings larger than 12 inches are normally fabricated from sections of pipe. Refer to Chapter 5 for a list of the commonly used PE fittings standards.

ASTM F2206 Standard Specification for Fabricated Fittings of Butt-Fused Polyethylene (PE) Plastic Pipe, Fittings, Sheet Stock, Plate Stock, or Block Stock.

All of these pipe and fittings standards specify the type and frequency of quality control tests that are required. There are

several steps during the manufacturing process that are closely monitored to ensure that the product complies with these rigorous standards. Some of these steps are discussed in the section of this chapter on quality control and assurance.

Pipe Extrusion

The essential aspects of a solid wall PE pipe manufacturing facility are presented in Figure 1. This section will describe the production of solid wall pipe from raw material handling, extrusion, sizing, cooling, printing, and cutting, through finished product handling. Details concerning profile wall pipe are also discussed in the appropriate sections.

Raw Materials Description

The quality of the starting resin material is closely monitored at the resin manufacturing site. As discussed in the chapter on test methods and codes in this handbook, a battery of tests is used to ensure that the resin is of prime quality. A certification sheet is sent to the pipe and fitting manufacturer documenting important physical properties such as melt index, density, ESCR (environmental stress crack resistance), SCG (slow crack growth), stabilizer tests, amongst others. The resin supplier and pipe manufacturer may agree upon additional tests to be conducted.

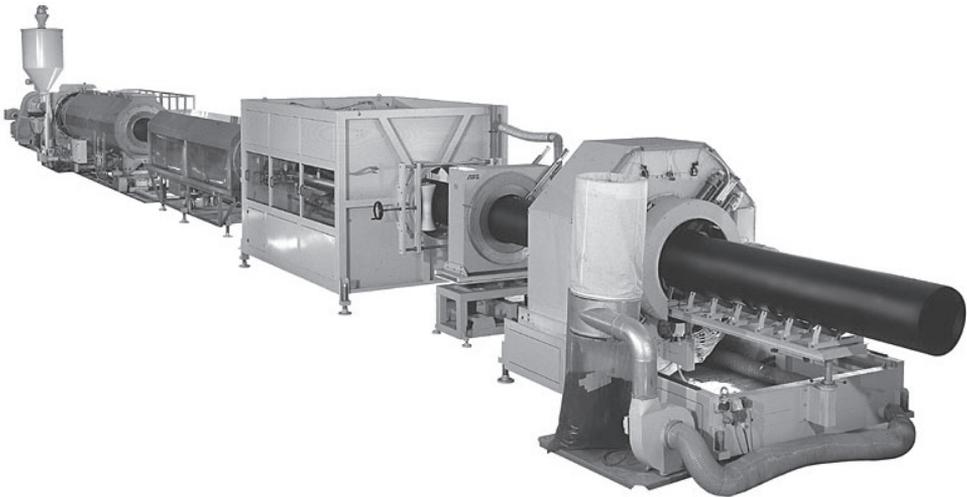


Figure 1 Typical Conventional Extrusion Line

Extrusion Line

The raw material, usually referred to as PE compound, is typically supplied to the pipe producer as non-pigmented pellets. PE pellets are stabilized for both heat and UV protection. Usually, color pigment is added to the pipe at the producer's facility. In North America, the most common colors are black and yellow. The choice of color will depend upon the intended application and the requirements of the pipe purchaser. Carbon black is the most common pigment used for water, industrial, sewer and above-ground uses. Yellow is reserved exclusively for natural gas applications, although black with yellow stripes is also permitted for this application. Other colors are used for telecommunications and other specialty markets.

All ASTM and many other industry standards specify that a PPI-listed compound shall be used to produce pipe and fittings for pressure pipe applications. A compound is defined as the blend of natural resin and color concentrate and the ingredients that make up each of those two materials. The pipe producer may not change any of the ingredients. In a listed compound, such as substituting a different color concentrate that could affect the long-term strength performance of the pipe. Any change to a listed formulation has to be pre-approved. These stringent requirements ensure that only previously tested and approved compounds are being used.

If the resin is supplied as a natural pellet, the pipe producer will blend a color concentrate with the resin prior to extrusion. In order to obtain a PPI Listing, each manufacturer producing pipe in this manner is required to submit data, according to ASTM 2837, to the PPI Hydrostatic Stress Board. A careful review of the data is made according to PPI Policy TR-3 ⁽⁵⁾ to assess the long-term strength characteristics of the in-plant blended compound. When those requirements are met, the compound qualifies for a Dependent listing and is listed as such in the PPI Publication TR-4 ⁽⁶⁾, which lists compounds that have satisfied the requirements of TR-3. Producers of potable water pipe are usually required to have the approval of the NSF International or an equivalent laboratory. NSF conducts un-announced visits during which time they verify that the correct compounds are being used to produce pipe that bears their seal.

Raw Materials Handling

After the material passes the resin manufacturer's quality control tests, it is shipped to the pipe manufacturer's facility in 180,000- to 200,000-pound capacity railcars, 40,000-pound bulk trucks, or 1000- to 1400-pound boxes.

Each pipe producing plant establishes quality control procedures for testing incoming resin against specification requirements. The parameters that are typically tested include: melt flow rate, density, moisture content and checks for

contamination. Many resin producers utilize statistical process control (SPC) on certain key physical properties to ensure consistency of the product.

Resin is pneumatically conveyed from the bulk transporters to silos at the plant site. The resin is then transferred from the silos to the pipe extruder by a vacuum transfer system. Pre-colored materials can be moved directly into the hopper above the extruder. If a natural material is used, it must first be mixed homogeneously with a color concentrate. The resin may be mixed with the color concentrate in a central blender remote from the extruder or with an individual blender mounted above the extruder hopper. The blender's efficiency is monitored on a regular basis to ensure that the correct amount of color concentrate is added to the raw material.

Extrusion Basics

The function of the extruder is to heat, melt, mix, and convey the material to the die, where it is shaped into a pipe⁽⁸⁾. The extruder screw design is critical to the performance of the extruder and the quality of the pipe. The mixing sections of the screw are important for producing a homogeneous mix when extruding blends. A typical extruder is shown in Figure 2.

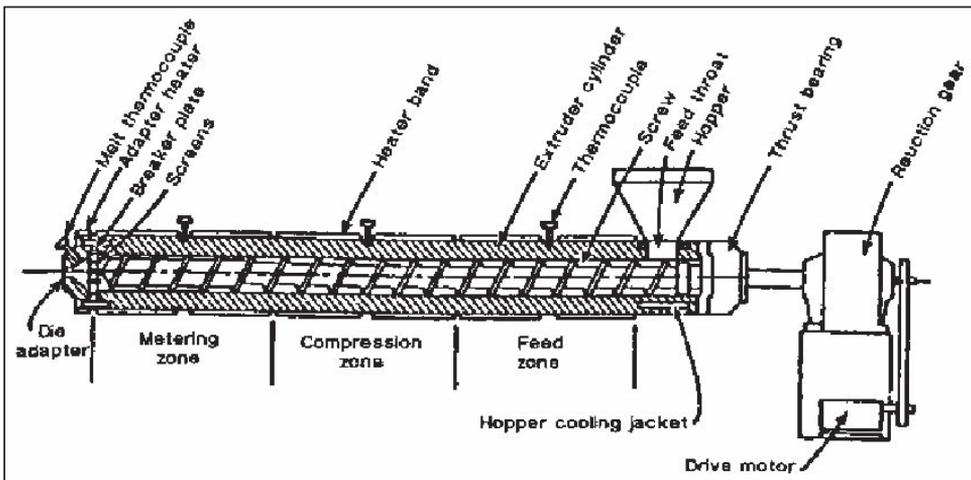


Figure 2 Typical Single-Stage, Single-Screw Extruder (Resin Flow from Right to Left)

There are many different types of screw designs⁽¹⁰⁾, but they all have in common the features shown in Figure 3. Each screw is designed specifically for the type of material being extruded.

The extruder screw operates on the stick/slip principle. The polymer needs to stick to the barrel so that, as the screw rotates, it forces the material in a forward direction.

In the course of doing this, the polymer is subjected to heat, pressure and shear (mechanical heating). The extent to which the material is subjected to these three conditions is the function of the screw speed, the barrel temperature settings and the screw design. The design of the screw is important for the production of high quality pipe.



Figure 3 Typical Extrusion Screw

If a natural resin and concentrate blend is used, the screw will also have to incorporate the colorant into the natural resin. Various mixing devices are used for this purpose as shown in Figure 4. They include mixing rings or pins, fluted or cavity transfer mixers, blister rings, and helix shaped mixers, which are an integral part of the screw.

The pipe extrusion line generally consists of the extruder, die, cooling systems, puller, printer, saw and take-off equipment. Each of these items will be addressed in the following section.

Figure 4 Typical Resin Mixing Devices

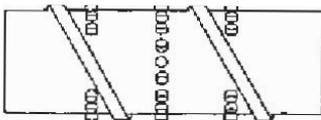


Figure 4.1 Mixing Pins

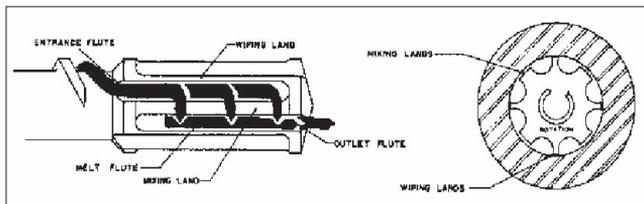


Figure 4.2 Fluted Mixer

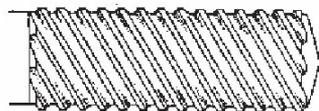


Figure 4.3 Helical Mixer

Extruders

An extruder is usually described by its bore size and barrel length. Pipe extruders typically have an inside diameter of 2 to 6 inches with barrel lengths of 20 to 32 times the bore diameter. The barrel length divided by the inside diameter is referred to as the L/D ratio. An extruder with an L/D ratio of 24:1 or greater provides adequate residence time to produce a homogeneous mixture.

The extruder is used to heat the raw material and then force the resulting melted polymer through the pipe extrusion die. The barrel of the machine has a series of four to six heater bands. The temperature of each band is individually controlled by an instrumented thermocouple. During the manufacturing process, the major portion of the heat supplied to the polymer is the shear energy generated by the screw and motor drive system. This supply of heat can be further controlled by applying cooling or heating to the various barrel zones on the extruder by a series of air or water cooling systems. This is important since the amount of heat that is absorbed by the polymer needs to be closely monitored. The temperature of the extruder melted polymer is usually between 390°F and 450°F, and it is also under high pressure (2000 to 4000 psi).

Breaker Plate/Screen Pack

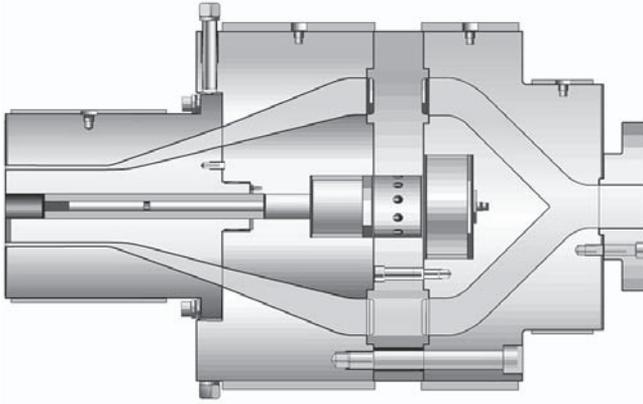
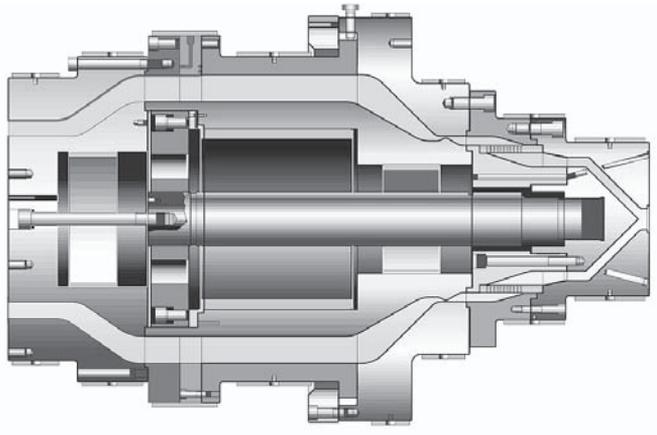
The molten polymer leaves the extruder in the form of two ribbons. It then goes through a screen pack which consists of one or more wire mesh screens, positioned against the breaker plate. The breaker plate is a perforated solid steel plate. Screen packs prevent foreign contaminants from entering the pipe wall and assist in the development of a pressure gradient along the screw. This helps to homogenize the polymer. To assist in the changing of dirty screen packs, many extruders are equipped with an automatic screen changer device. It removes the old pack while it inserts the new pack without removing the die head from the extruder.

Die Design

The pipe extrusion die supports and distributes the homogeneous polymer melt around a solid mandrel, which forms it into an annular shape for solid wall pipe⁽⁹⁾. The production of a profile wall pipe involves extruding the molten polymer through a die which has a certain shaped profile.

The die head is mounted directly behind and downstream of the screen changer unless the extruder splits and serves two offset dies.

There are two common types of die designs for solid wall pipe; the spider die design and the basket die design. They are illustrated in Figure 5. These designs refer to the manner in which the melt is broken and distributed into an annular shape and also the means by which the mandrel is supported.

Figure 5 Typical Pipe Dies**Figure 5.1** Pipe Die with Spider Design**Figure 5.2** Pipe Die with Basket Design

In the spider die (Figure 5.1), the melt stream is distributed around the mandrel by a cone which is supported by a ring of spokes. Since the melt has been split by the spider legs, the flow must be rejoined.

Flow lines caused by mandrel supports should be avoided. This is done by reducing the annular area of the flow channel just after the spider legs to cause a buildup in die pressure and force the melt streams to converge, minimizing weld or spider lines. After the melt is rejoined, the melt moves into the last section of the die, called the land.

The land is the part of the die that has a constant cross-sectional area. It reestablishes a uniform flow and allows the final shaping of the melt and also allows the resin a

certain amount of relaxation time. The land can adversely affect the surface finish of the pipe if it is too short in length. Typical land lengths are 15 to 20 times the annular spacing.

The basket design (Figure 5.2) has an advantage over the spider die concerning melt convergence. The molten polymer is forced through a perforated sleeve or plate, which contains hundreds of small holes. Polymer is then rejoined under pressure as a round profile. The perforated sleeve, which is also called a screen basket, eliminates spider leg lines.

Pipe Sizing

The dimensions and tolerances of the pipe are determined and set during the sizing and cooling operation. The sizing operation holds the pipe in its proper dimensions during the cooling of the molten material. For solid wall pipe, the process is accomplished by drawing the hot material from the die through a sizing sleeve and into a cooling tank. Sizing may be accomplished by using either vacuum or pressure techniques. Vacuum sizing is generally the preferred method.

In the vacuum sizing system, molten extrudate is drawn through a sizing tube or rings while its surface is cooled enough to maintain proper dimensions and a circular form. The outside surface of the pipe is held against the sizing sleeve by vacuum. After the pipe exits the vacuum sizing tank, it is moved through a second vacuum tank or a series of spray or immersion cooling tanks.

Figure 6 External Sizing Systems

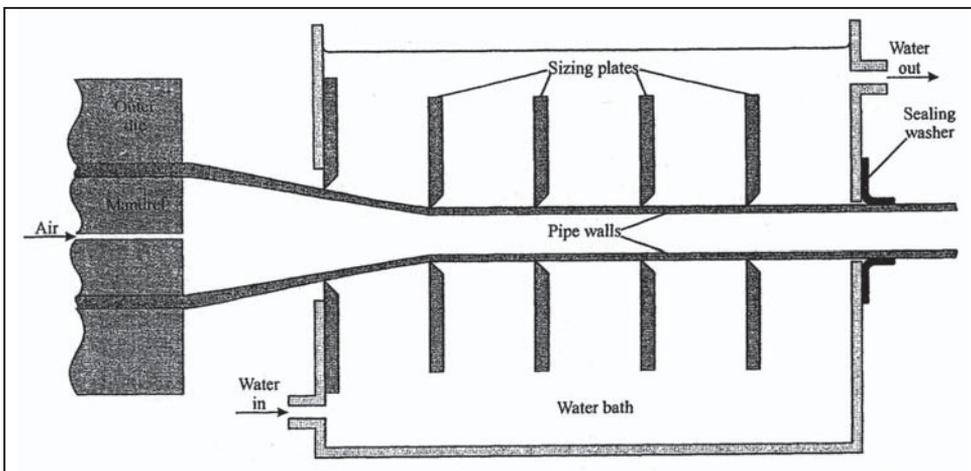


Figure 6.1 Vacuum Tank Sizing⁽¹¹⁾

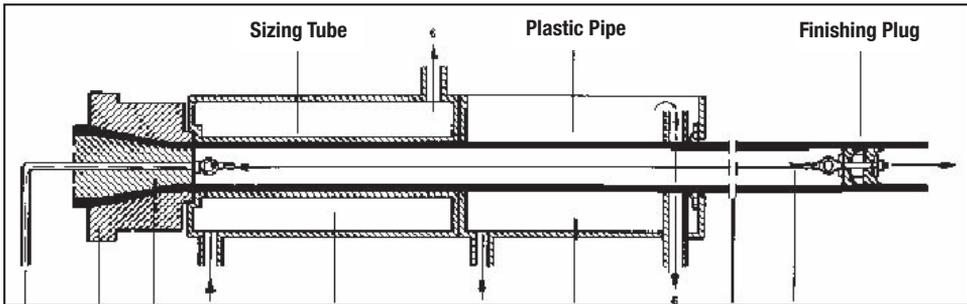


Figure 6.2 Internal (Pressure) Sizing for Small and Medium Pipe Diameters

In the pressure sizing system, a positive pressure is maintained on the inside of the pipe by the use of a plug attached to the die face by a cable or, on very small bore pipe, by closing or pinching off the end of the pipe. The pressure on the outside of the pipe remains at ambient and the melt is forced against the inside of the calibration sleeve with the same results as in the vacuum system.

The production of very large diameter profile pipe, up to 10 feet in diameter, uses mandrel sizing. In one form of this process, the extruded profile is wrapped around a mandrel. As the mandrel rotates, the extruded profile is wrapped such that each turn overlaps the previous turn. In some other techniques, the turns are not overlapped. A typical profile wall PE pipe is shown in Figure 7.

Figure 7 Typical PE Profile Wall Pipe from ASTM Standard F894

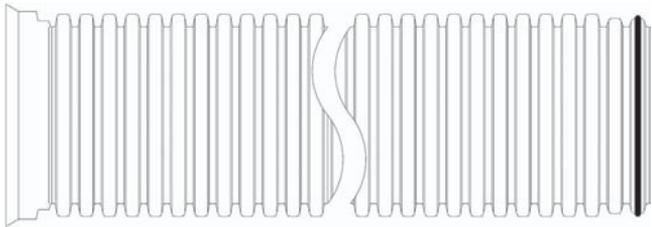


Figure 7.1 Laying Lengths



Figure 7.2 Typical Profile Wall Section Showing Bell End (right) and Spigot End (left)

Cooling

For either the vacuum or pressure sizing technique, the pipe must be cool enough so that it maintains its circularity before it exits the cooling tank. Various methods of cooling are utilized to remove the residual heat out of the PE pipe. Depending upon the pipe size, the system may use either total immersion or spray cooling. Spray cooling is usually applied to large diameter pipe where total immersion would be inconvenient. Smaller diameter pipe is usually immersed in a water bath. Cooling water temperatures are typically in the optimum range of 40° to 50°F (4° to 10°C). The total length of the cooling baths must be adequate to cool the pipe below 160°F (71°C) in order to withstand subsequent handling operations.

Residual stresses generated by the cooling process within the pipe wall are minimized by providing annealing zones.⁽⁴⁾ These zones are spaces between the cooling baths which allow the heat contained within the inner pipe wall to radiate outward and anneal the entire pipe wall. Proper cooling bath spacing is important in controlling pipe wall stresses. Long-term pipe performance is improved when the internal pipe wall stresses are minimized.

Pullers

The puller must provide the necessary force to pull the pipe through the entire cooling operation. It also maintains the proper wall thickness control by providing a constant pulling rate. The rate at which the pipe is pulled, in combination with the extruder screw speed, determines the wall thickness of the finished pipe. Increasing the puller speed at a constant screw speed reduces the wall thickness, while reducing the puller speed at the same screw speed increases the wall thickness.

Standards of ASTM International and other specifications require that the pipe be marked at frequent intervals. The markings include nominal pipe size, type of plastic, SDR and/or pressure rating, and manufacturer's name or trademark and manufacturing code. The marking is usually ink, applied to the pipe surface by an offset roller. Other marking techniques include hot stamp, ink jet and indent printing. If indent printing is used, the mark should not reduce the wall thickness to less than the minimum value for the pipe or tubing, and the long-term strength of the pipe or tubing must not be affected. The mark should also not allow leakage channels when gasket or compression fittings are used to join the pipe or tubing.

Take-off Equipment

Most pipe four inches or smaller can be coiled for handling and shipping convenience. Some manufacturers have coiled pipe as large as 6 inch. Equipment allows the pipe to be coiled in various lengths. Depending upon the pipe

diameter, lengths of up to 10,000 feet are possible. This is advantageous when long uninterrupted lengths of pipe are required - for example, when installing gas and water pipes.

Saw Equipment and Bundling

Pipe four inches or more in diameter is usually cut into specified lengths for storage and shipping. Typical lengths are 40 to 50 feet, which can be shipped easily by rail or truck. The pipe is usually bundled before it is placed on the truck or railcar. Bundling provides ease of handling and safety during loading and unloading.

Fittings Overview

The PE pipe industry has worked diligently to make PE piping systems as comprehensive as possible. As such, various fittings are produced which increase the overall use of the PE piping systems. Some typical fittings are shown in Figure 8.

PE fittings may be injection molded, fabricated or thermoformed. The following section will briefly describe the operations of each technique.

Injection Molded Fittings

Injection molded PE fittings are manufactured in sizes through 12-inch nominal diameter. Typical molded fittings are tees, 45° and 90° elbows, reducers, couplings, caps, flange adapters and stub ends, branch and service saddles, and self-tapping saddle tees. Very large parts may exceed common injection molding equipment capacities, so these are usually fabricated.

Equipment to mold fittings consists of a mold and an injection molding press, as shown in Figure 9. The mold is a split metal block that is machined to form a part-shaped cavity in the block. Hollows in the part are created by core pins shaped into the part cavity. The molded part is created by filling the cavity in the mold block through a filling port, called a gate. The material volume needed to fill the mold cavity is called a shot.

The injection molding press has two parts; a press to open and close the mold block, and an injection extruder to inject material into the mold block cavity. The injection extruder is similar to a conventional extruder except that, in addition to rotating, the extruder screw also moves lengthwise in the barrel. Injection molding is a cyclical process. The mold block is closed and the extruder barrel is moved into contact with the mold gate. The screw is rotated and then drawn back, filling the barrel ahead of the screw with material. Screw rotation is stopped and the screw is rammed forward, injecting molten material into the mold cavity under high pressure. The

part in the mold block is cooled by water circulating through the mold block. When the part has solidified, the extruder barrel and mold core pins are retracted, the mold is opened, and the part is ejected.

Typical quality inspections are for knit line strength, voids, dimensions and pressure tests. A knit line is formed when the molten PE material flows around a core pin and joins together on the other side. While molding conditions are set to eliminate the potential for voids, they can occur occasionally in heavier sections due to shrinkage that takes place during cooling. Voids can be detected nondestructively by using x-ray scans. If this is not available, samples can be cut into thin sections and inspected visually.

Figure 8 Typical PE Pipe Fittings

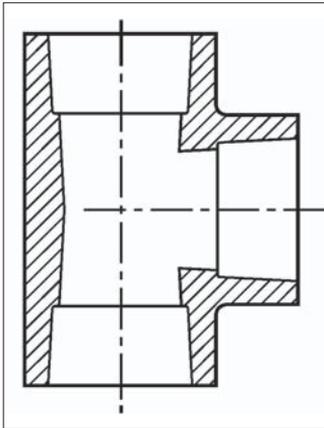


Figure 8.1 Socket Tee

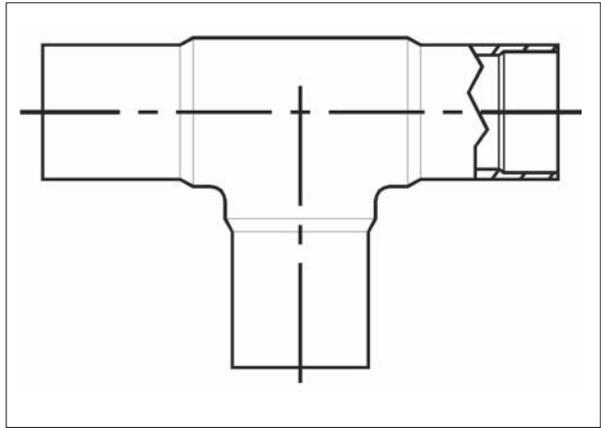


Figure 8.2 Butt Tee

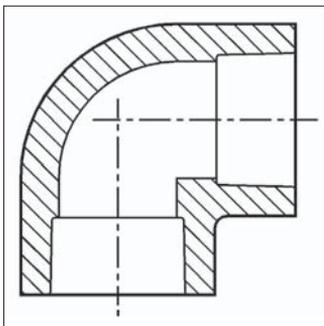


Figure 8.3 90° Socket Elbow

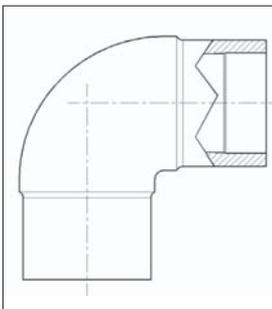


Figure 8.4 90° Butt Elbow

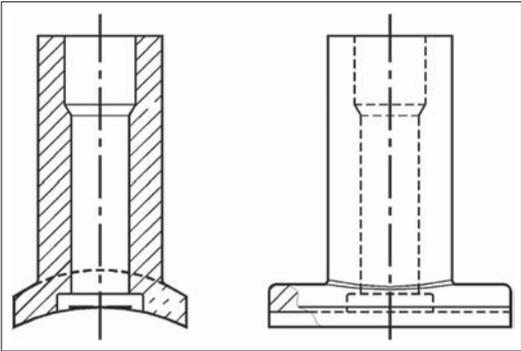


Figure 8.5 Saddle Fusion Fittings

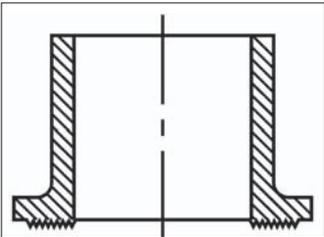


Figure 8.6 Butt Flange Adapter/Stub End

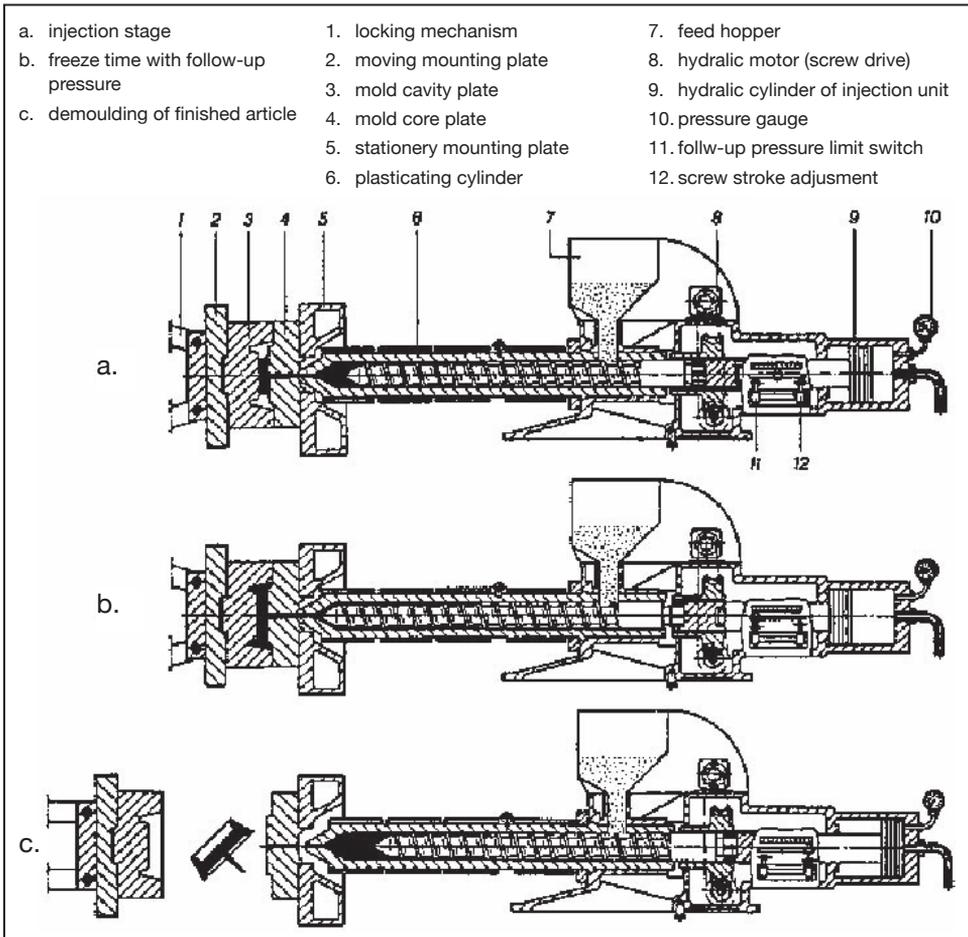


Figure 9 Construction and Mode of Operation of a Reciprocating Screw Injection Unit
(Courtesy of Hoechst Celanese Corporation)

Fabricated Fittings

Fully pressure-rated, full bore fabricated fittings are available from select fittings fabricators. Fabricated fittings are constructed by joining sections of pipe, machined blocks, or molded fittings together to produce the desired configuration. Components can be joined by butt or socket heat fusion, electrofusion, hot gas welding or extrusion welding techniques. It is not recommended to use either hot gas or extrusion welding for pressure service fittings since the resultant joint strength is significantly less than that of the other heat fusion joining methods.

Fabricated fittings designed for full pressure service are joined by heat fusion and must be designed with additional material in regions of sharp geometrical changes,

regions that are subject to high localized stress. The common commercial practice is to increase wall thickness in high-stress areas by fabricating fittings from heavier wall pipe sections. The increased wall thickness may be added to the OD, which provides for a full-flow ID; or it may be added to the ID, which slightly restricts ID flow. This is similar to molded fittings that are molded with a larger OD, heavier body wall thickness. If heavy-wall pipe sections are not used, the conventional practice is to reduce the pressure rating of the fitting. The lowest-pressure-rated component in a pipeline determines the operating pressure of the piping system.

Various manufacturers address this reduction process in different manners. Reinforced over-wraps are sometimes used to increase the pressure rating of a fitting. Encasement in concrete, with steel reinforcement or rebar, is also used for the same purpose. Contact the fitting manufacturer for specific recommendations.

Very large diameter fittings require special handling during shipping, unloading, and installation. Precautions should be taken to prevent bending moments that could stress the fitting during these periods. Consult the fittings manufacturer for specifics. These fittings are sometimes wrapped with a reinforcement material, such as fiberglass, for protection.

Thermoformed Fittings

Thermoformed fittings are manufactured by heating a section of pipe and then using a forming tool to reshape the heated area. Examples are sweep elbows, swaged reducers, and forged stub ends. The area to be shaped is immersed in a hot liquid bath and heated to make it pliable. It is removed from the heating bath and reshaped in the forming tool. Then the new shape must be held until the part has cooled.

Electrofusion Couplings

Electrofusion couplings and fittings are manufactured by either molding in a similar manner as that previously described for butt and socket fusion fittings or manufactured from pipe stock. A wide variety of couplings and other associated fittings are available from ½" CTS thru 28" IPS. Fittings are also available for ductile iron sized PE pipe. These couplings are rated as high as FM 200.

Electrofusion fittings are manufactured with a coil-like integral heating element. These fittings are installed utilizing a fusion processor, which provides the proper energy to provide a fusion joint stronger than the joined pipe sections. All electrofusion fittings are manufactured to meet the requirements of ASTM F-1055.

Injection Molded Couplings

Some mechanical couplings are manufactured by injection molding in a similar manner as previously described for butt and socket fusion fittings. The external

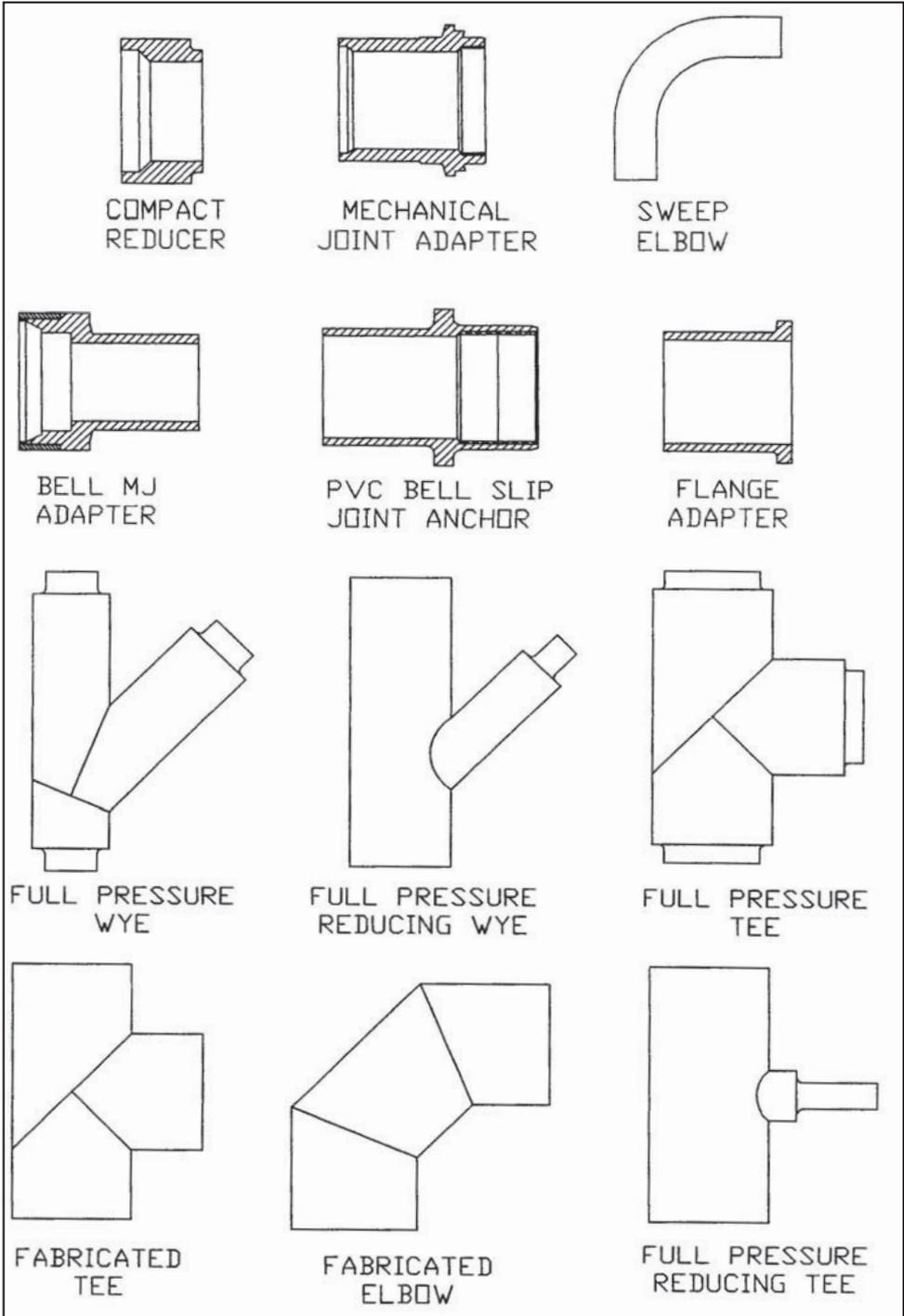


Figure 10 Typical Fabricated Fittings

coupling body is typically injection molded and upon final assembly will include internal components such as steel stiffeners, o-rings, gripping collets, and other components depending upon the design. A wide variety of coupling configurations are available including tees, ells, caps, reducers, and repair couplings. Sizes for joining PE pipe and tubing are typically from ½" CTS through 2" IPS. All injection molded couplings are manufactured to meet the requirements of ASTM D2513.

Quality Control/Quality Assurance Testing

Quality is engineered into the pipe and fitting product during the entire manufacturing process. The three phases of quality control for the pipe manufacturer involve the incoming raw material, the pipe or fitting production and the finished product. The combination of all three areas ensures that the final product will fulfill the requirements of the specification to which it was made.

Testing the incoming resin is the first step in the quality control program. It is usually checked for contamination, melt flow rate and density. Any resin that does not meet the raw material specification is not used for the production of specification-grade pipe or fitting.

During the manufacturing step, the pipe or fitting producer routinely performs quality control tests on samples. This verifies that proper production procedures and controls were implemented during production.

Once the product has been produced, it undergoes a series of quality assurance tests to ensure that it meets the minimum specifications as required by the appropriate standard. (See Handbook Chapter on Test Methods and Codes.)

The manufacturing specifications for piping products list the tests that are required. There are several quality control tests that are common in most ASTM PE standards. For gas service piping systems, refer to PPI Technical Report TR-32 ⁽⁷⁾ for a typical quality control program for gas system piping, or to the AGA Plastic Pipe Manual for Gas Service ⁽¹⁾. The typical QC/QA tests found in most standards are described below.

Workmanship, Finish, and Appearance

According to ASTM product specifications, the pipe, tubing, and fittings shall be homogeneous throughout and free of visible cracks, holes, foreign inclusions, blisters, and dents or other injurious defects. The pipe tubing and fittings shall be as uniform as commercially practicable in color, opacity, density and other physical properties.

Dimensions

Pipe diameter, wall thickness, ovality, and length are measured on a regular basis to insure compliance with the prevailing specification. All fittings have to comply with the appropriate specification for proper dimensions and tolerances. All measurements are made in accordance with ASTM D2122, Standard Test Method of Determining Dimensions of Thermoplastic Pipe and Fittings⁽²⁾.

Physical Property Tests

Several tests are conducted to ensure that the final pipe product complies to the applicable specification. Depending upon the specification, the type and the frequency of testing will vary. More details about industry standard requirements can be found in the chapter on specifications, test methods and codes in this Handbook.

The following tests, with reference to the applicable ASTM standard⁽²⁾, are generally required in many product specifications such as natural gas service. The following list of tests was taken from the American Gas Association Manual for Plastic Gas Pipe⁽¹⁾ to serve as an example of typical tests for gas piping systems.

ASTM TESTS

Sustained Pressure	D1598
Burst Pressure	D1599
Apparent Tensile Strength	D2290

Neither the sustained pressure test or the elevated temperature pressure test are routine quality assurance tests. Rather, they are less frequently applied tests required by the applicable standards to confirm and assure that the established process system and materials being used produce quality product meeting the requirements of the standard.

There are other tests that are used that are not ASTM test methods. They are accepted by the industry since they further ensure product reliability. One such test, required by applicable AWWA Standards, is the Bend-Back Test⁽¹⁾ which is used to indicate inside surface brittleness under highly strained test conditions. In this test, a ring of the pipe is cut and then subjected to a reverse 180-degree bend. Any signs of surface embrittlement, such as cracking or crazing, constitute a failure. The presence of this condition is cause for rejection of the pipe.

Quality Assurance Summary

Through the constant updating of industry standards, the quality performance of the PE pipe and fitting industry is continually evolving. Each year, PPI and ASTM work to improve standards on plastic pipe which include the latest test methods and recommended practices. Resin producers, pipe extruders, and fittings manufacturers incorporate these revisions into their own QA/QC practices to insure compliance with these standards. In this way, the exceptional performance and safety record of the PE pipe industry is sustained.

Summary

This chapter provides an overview of the production methods and quality assurance procedures used in the manufacture of PE pipe and fittings. The purpose of this chapter is to create a familiarity with the processes by which these engineered piping products are made. Through a general understanding of these fundamental processes, the reader should be able to develop an appreciation for the utility and integrity of PE piping systems.

References

1. AGA *Plastic Pipe Manual for Gas Service*. (2001). Catalog No. XR0185, American Gas Association, Arlington, VA.
2. *Annual Book of ASTM Standards*. (2005). Volume 08.04, Plastic Pipe and Building Products, American Society for Testing and Materials, Philadelphia, PA.
3. Kamp, W., & H. D. Kurz. (1980). Cooling Sections in Polyolefin Pipe Extrusion, *Kunststoffe 70*, pp. 257-263, English Translation.
4. Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Rating for Thermoplastic Piping Materials or Pipe (2005). Report TR-3, Plastics Pipe Institute, Irving, TX.
5. PPI Listing of Hydrostatic Design Basis (HDB), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe (2005). Report TR-4, Plastics Pipe Institute, Irving, TX.
6. Recommended Minimum In-Plant Quality Control Program for Production of PE Gas Distribution Piping Systems. (1989). Report TR-32, Plastics Pipe Institute, Irving, TX.
7. Schiedrum, H. O. (1974). The Design of Pipe Dies, *Plastverarbeiter*, No. 10, English Translation.
8. Rauwendaal, C. (1986). *Polymer Extrusion*, MacMillan Publishing Company, Inc., New York, NY.
9. *Screw and Barrel Technology*. (1985). Spirex Corporation, Youngstown, OH.
10. Peacock, Andrew J. (2000). *Handbook of PE*, Marcel Decker, Inc. New York, NY.