Chapter 11

Electrofusion Welding

PROCESS

Electrofusion (E/F) welding is commonly used in joining polyethylene pipes; joints obtained are fluid tight and capable of withstanding large loads for over 50 years. Cylindrical or wrap-around electrofusion couplers with heating elements on the inside diameter can be used to join pipes of over 20 cm (7.9 in.) in diameter. In electrofusion welding, electricity applied to a heating element heats the heating element and the surrounding thermoplastic in the coupler and pipe, resulting in melting and flow of the thermoplastic material, and a weld forms upon cooling. [555]

Electrofusion couplers can be heated by resistance wire, induction (wire or ferrite particles - see Induction Welding), radiofrequency radiation, or conductive polymers, such as conductive ultra high molecular weight polyethylene (CUHMWPE). Resistance wire is the most prevalent; CUHMWPE is the newest type of coupler and is used in wrap-around electrofusion couplers. The diameter of an E/F coupler is usually greater than that of the pipe it is used for joining, so that the coupler fits around the outside of the pipe, leaving a small gap between the coupler and pipe. Couplers usually have two separate fusion zones, where heating occurs, separated by a cold zone (Figure 11.1). Additional cold zones are at either end of the coupler. Heat is generated by passing current through the terminal pins on either side of the coupler. [572]

Joint formation in electrofusion welding consists of four stages. In the incubation stage (I), heat is applied to the coupler clamped onto the pipe; the PE in the coupler expands, filling the gap between the pipe and coupler. Contact of the coupler with the pipe then heats the PE pipe above its melt temperature (120 - 135°C for pipe grade resin), and the two pipe surfaces to be welded begin to melt. In the joint formation stage, melt from the coupler combines with that from the pipe, and a stable melt pool is created. Molten PE is prevented from extruding out of the joint by cold zones in the coupler, and the low thermal conductivity of PE restricts resin melting to the fusion zones. Joint strength of the weld at this stage is low, producing brittle failures due to limited intermolecular diffusion across the weld interface. High molecular weight molecules begin to diffuse across the weld interface in the joint consolidation stage (II); in this stage, joint strength increases with increasing heating or fusion time, and the failure mode in strength tests changes from brittle to ductile. Excessive fusion times, however, result in polymer degradation. Current is terminated in the joint cooling stage (III), and the weld slowly cools under clamping pressure. Macromolecular diffusion across the weld interface occurs in this stage, and polymer chain entanglements across the interface create a high strength weld. As cooling continues, PE

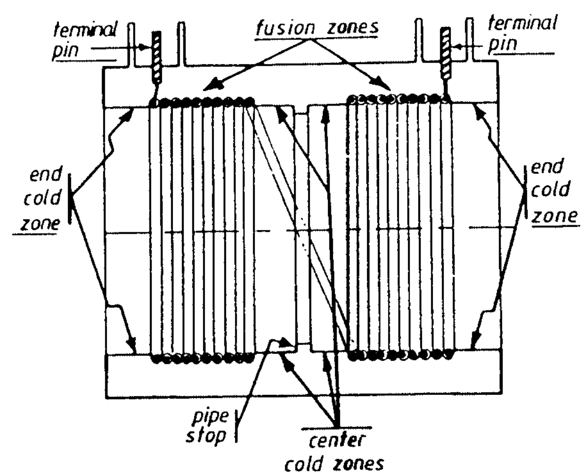

Figure 11.1 Design of an electrofusion coupler. The heating element is located in the two fusion zones, separated by two cold zones at the center of the coupler; two more cold zones are on either end of the coupler. Cold zones prevent melt from extruding out of the joint, and pipe stops provide for control of the weld displacement. Current is generated by connecting terminal pins to an electrical source.

recrystallizes, beginning in the areas adjacent to the cold zones. As cooling and crystallization proceed inward, the PE contracts, and the pipe shrinks in diameter. [638]

Pipe preparation is necessary for successful welding. Pipes must be thoroughly scraped to remove dirt, contamination, and oxidation layers in order to allow mixing of melt from the pipes and coupler during welding. Pipe ends must be cut square and inserted into cylindrical couplers so that pipe ends are at the center of the coupler (Figure 11.2). This placement ensures proper functioning of the coupler cold zones. For wrap-around couplers, pipe ends must be positioned within 1.25 cm (0.49 in.) of each other; the coupler is then wrapped around the pipe ends (Figure 11.3), and chains are wrapped around the entire assembly and clamped onto the coupler and pipes. Pipes must be securely clamped throughout all stages of welding for strong joint formation. Cylindrical E/F couplers must be preheated. [555, 638]

PROCESSING PARAMETERS

Parameters important in electrofusion welding include pipe and joint thickness, voltage applied, heating or fusion time, initial and ambient temperatures (since electrofusion welding is usually performed outdoors), cooling time and method (ambient air, fan, dry ice, water), and wire depth and length. [554]

In experiments with simulated electrofusion joints, weld strength increased with increasing heating time, then decreased. Tensile

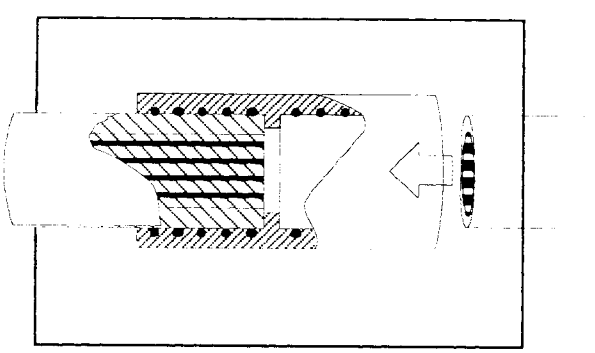

Figure 11.2 Axial insertion of a pipe into a cylindrical electrofusion coupler.

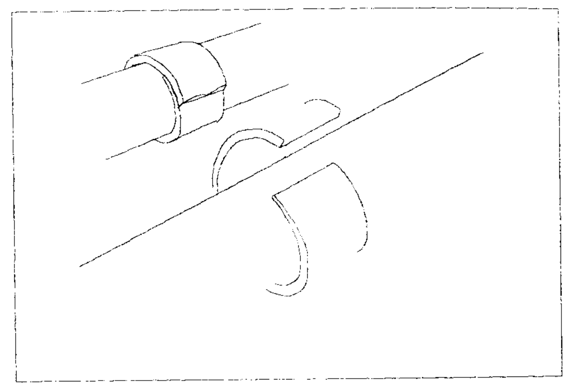

Figure 11.3 Placement of a wrap-around coupler around pipes being joined.

yield strength increased dramatically with heating times up to about 80 seconds at power levels of 5.2 W/cm^2, then decreased dramatically with further increases. At a power level of 3.0 W/cm^2, optimal fusion time was approximately 150 seconds, with tensile strength decreasing slightly at longer heating times. Similar results were obtained using an elevated temperature test, in which failure was induced by slow propagation of a brittle crack. Time to failure at a stress level of 3.9 MPa in an 80^{o}C environment increased dramatically with a power level of 5.2 W/cm^2, to a heating time of ~60 seconds, then decreased dramatically at longer heating times. At a lower power level (3.0 W/cm^2), optimum heating time was ~175 seconds, with a gradual decrease in strength at longer heating times. In experimental studies, the toughness parameter (Kc) of coupons cut from E/F joints obtained with double cantilever beam cleavage tests increased exponentially with increasing heating time up to ~220 seconds; longer heating times were not studied. Although PE used in pipes is thermally stabilized, extended exposure to high heat, either through long heating times or high power, leads to stabilizer consumption; polymer degradation then occurs, resulting in a loss of joint strength. [638]

In experiments with specimens cut from polyethylene pipes, tensile strength was dependent on both power and heating time; maximum tensile strength, with time to failure of ≥ 100 hours, was obtained at combinations of high power and short heating times or low power and long heating times. [554]

MATERIALS

Polyethylene pipes range in diameter from 1 cm (2.54 in.) to 2 m (26.4 ft.); electrofusion welding has been used to join pipes from ≤ 10 cm (3.9 in.) to 1.2 m (4.0 ft.). Large diameter pipes can have significant out-of-round areas, resulting in the formation of voids. Melt flow must flow into voids for optimum joint strength. In addition to polyethylene pipes, electrofusion welding is used to join thermoplastic liners of steel pipes, either in the shop or in the field. Liners are composed of materials such as PE, polyvinyl chloride (PVC), or polyetheretherketone (PEEK); when welding the steel pipe, precautions must be taken to protect the plastic liner from the high temperatures (<1000°C) used for welding steel. [561, 554, 555]

EQUIPMENT

Couplers for electrofusion welding are composed of a heating element and a thermoplastic polymer. Heating elements can be resistant wire, ferrite particles (induction heating), radiofrequency energy, or conductive polymers. Wires in heating elements are usually coated with the thermoplastic polymer used to mold the body of the fitting. [638, 572]

Resistant wire, induction, radiofrequency, and some conductive polymer heating elements are used in cylindrical couplers. With these couplers, the pipe ends are inserted into the coupler for welding; axial movement of the pipe is necessary. Small diameter pipes can be picked up and bent to allow for insertion, but extra pipe length is necessary to provide pressure during welding and cooling. Long heating times are necessary due to a lack of intimate contact between the pipe and the coupler. Large diameter pipes (≥ 30 cm) are not easily inserted; wrap-around couplers are used to weld these pipes. [555]

Flexible wrap-around couplers have conductive polymers such as CUHMWPE as heating elements. CUHMWPE in the form of a tape or thin sheet is flexible and can conform to different surfaces. It is capable of very rapid heating, and pipes ranging from 11.4 cm (4.48 in.) to 1.2 m (4.0 ft.) in diameter can be joined. Rigid pipe and coupler walls are maintained by a low melt depth (~0.1 cm, 0.039 in.). CUHMWPE expands by > 20% at 200°C, producing a hydraulic force within the pipe and coupler interface that squeezes melt into voids. Tape length can be changed without changing voltage or power density; total power or current does change with tape length. When current is applied, heat escapes from the two surfaces of the tape, up to a critical maximum tape thickness of < 0.15 cm (0.059 in.), and polymer degradation in the tape is prevented. Polymer degradation can occur at greater thicknesses due to heat retention in the tape. CUHMWPE couplers are generally heated for 3 minutes at 2 W/cm^2 power, a slow heating rate that is necessary due to the gap between pipe and coupler; however, temperatures above 200°C are reached in 15 - 30 seconds. Higher power densities (30 - 80 W/cm^2) can be achieved if the heater and joining surfaces are in intimate contact. Pipes in intimate contact can reach 200°C in three seconds (flash welding). Under these conditions, heat transfer to the substrates is critical; temperatures above 300°C cause almost instantaneous polymer degradation. [572, 555]

Electrofusion welding can be microprocessor-controlled or operator-controlled. In microprocessor-controlled equipment, welding can be performed initially at low power to fill gaps, then at higher power for melting. Welding is usually performed for a specific time. Because electrofusion welding is usually performed outdoors, timed welds may not be adequate. The temperature difference between the sunny and shady sides of the pipe can be as high as 100°C, and melt flow on the cold side can lag behind melt flow of the hotter side by 30 seconds to over a minute. [555]

Visual indicators can be used to control the welding process. Most E/F couplers have a pop-out indicator (Figure 11.4) that can be monitored by the operator. When voids are filled with melt, further expansion causes stems in the coupler to pop out, signaling the operator that power can be terminated. When pipes with diameters larger than 30 cm (11.8 in.) are being welded, multiple indicators are necessary, due to the presence of voids, temperature differences on different sides of the pipe, and out-of-round coupler/pipe profiles. [555]

ADVANTAGES AND DISADVANTAGES

Electrofusion welding is a simple process with low energy and equipment requirements. Pipes are easily assembled outside under varying weather conditions. When used for other products, cost reductions can be achieved by shipping products unassembled; final products can be assembled when received. With flash welding, thin sections can be welded. Since only the surface is heated, not the bulk material, no sink marks or color distortions are produced, and loads are spread uniformly across substrates. When E/F welding is used to weld dissimilar materials, the heating element can be reactivated to separate materials for recycling.

Hot tool welding and mechanical fastening are commonly used to join PE pipes. For hot tool welding, axial pipe movement is necessary. For mechanical fastening, flanges and “spool pieces” for interconnections are needed; costs of extra materials ranges from $0.20 to $15.00 per millimeter of pipe diameter. Lifetime of mechanical joints is only 3 - 5 years, due to corrosion, so that joint repair is necessary.

A high quality/cost ratio can be achieved using wrap-around electrofusion couplers. One coupler can accommodate a variety of pipe sizes, and no metallic substances are present in the bond line after welding. The joint is fused at or near the ultimate tensile strength of the pipe, with efficient use of manpower and off-the-shelf availability of couplers. Pipes can be visually inspected after welding. Scraping or abrading marks indicates proper pipe preparation, positioning marks verify the correct positioning of coupler and pipes, and pop-out indicators show that proper clamping and fusion was achieved. [555, 572]

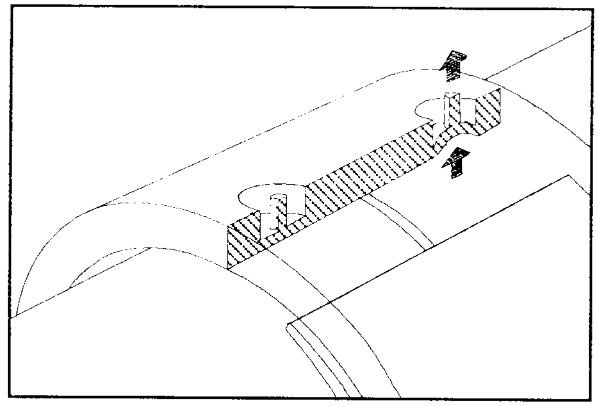

Figure 11.4 Multiple pop-out indicators on an electrofusion coupler, before and after power is terminated.

APPLICATIONS

Electrofusion welding is primarily used in joining polyethylene pipes used in the oil, gas, marine, and mining industries and for general construction. Uses include drainage, sewage, and methane recovery. Wrap-around electrofusion couplers are useful for pipes greater than 30 cm (11.8 in.) in diameter and when hot tool welding cannot be used. [555, 561]