Influence of Joining on the Fatigue and Fracture Behavior of High Density Polyethylene Pipe

H. Chen, R.J. Scavuzzo, and T.S. Srivatsan

Polyethylene pipes have been used in a spectrum of corrosion-critical applications, including distribution systems for oil, gas, water, and chemicals. In this paper, the influence of joining on bending fatigue and fracture behavior of high density polyethylene pipe is presented and discussed, and performance is compared with a plain unwelded counterpart. High density polyethylene pipes were joined using electro-fusion and butt-fusion techniques. Stiffness and strength of the electro-fusion joined pipe was far inferior to the butt-fusion and the plain unwelded pipe. Tensile failure of the butt-fusion joined specimen occurred at the fusion zone, while tensile failure of the electro-fusion joined pipe specimen occurred at the fusion joint. Bending fatigue resistance, quantified in terms of life to failure, of the pressurized pipe was superior to that of the unpressurized pipe. The fatigue resistance of the butt-fusion joined specimen was superior to that of the electro-fusion joined pipe specimen. The unwelded plain polyethylene pipe had bending fatigue resistance superior to that of the butt-fusion joined counterpart. Rationale for the differences observed in bending fatigue life is presented, and intrinsic differences in failure characteristics are highlighted.

Keywords fatigue, fracture, joining, polyethylene

1. Introduction

The gas research institute (GRI) has sponsored research and development efforts during the last two decades into understanding the mechanical response of high-density polyethylene (HDPE) pipe for use as transmission pipe lines for natural gases. Because HDPE is fairly resistant to chemical attack at temperatures below 60 °C (140 °F), it is also used as a candidate for other applications such as water liners and piping in chemical processing plants to transmit liquid chemicals and slurries. In applications involving the transport of slurries, the HDPE pipes showed a tendency to outlast conventional steel by a factor of three to one or four to one. Furthermore, inertness of the pipe obviates the need for catalytic protection required for most steel pipes (Ref 1).

One of the most difficult aspects pertaining to the potential widespread use of HDPE pipes is joining sections of straight pipe, elbows, and fittings, such as outlet saddles. Unlike classic polyvinyl chloride (PVC) pipes, HDPE pipes cannot be joined using solvents. They can, however, be joined by fusion. There are a variety of fusion joints available for HDPE pipes. Most often, the straight pipe is butt-fused using a hot plate technique that has been developed, validated, and widely used in the industrial sector. Welders involved in fusion joining of these pipes are meticulously trained in the art and technique of joining before being certified for welding HDPE pipe for a spectrum of applications. In this research program, butt-fusion joined specimens were initially prepared in a facility lacking in qualified technicians. This resulted in all but one of the specimens failing at the end of the first bending cycle. To obviate any influences caused by improper joining, all specimens were rewelded to precision by a qualified welder and subsequently deformed in bending. Besides butt welding, socket fusion is also widely used to join straight pipes. Again, there are a number of methods used to fuse these socket joints together. One method, which makes use of wires imbedded in the joint and melts the plastic by electric resistance heating, is examined in this investigation.

The thermal expansion coefficient of HDPE and other contending thermoplastic materials is almost an order of magnitude greater than that of steel. For a 10 °C (18 °F) change in temperature, a span of 33 m of HDPE pipe will expand about 0.07 to 0.08 m (7 to 8 cm). Consequently, cyclic variation in the temperature of piping systems can result in the development of bending loads. Also, chemical and nuclear plants are required, in many states, to withstand dynamic loading arising from earthquakes. These inertia forces can induce cyclic bending stresses in the piping systems. Failure due to fatigue, especially of the joints, must be critically examined. Research in the late 1970s and early 1980s, sponsored by the GRI, focused on examining the mechanical properties of HDPE pipe and pipe joints (Ref 2-5). Many of the fatigue tests conducted were based on cyclic internal pressure. A few programs included cyclic bending of the pipe (Ref 6-9).

The primary objective of this study was to systematically evaluate the tensile and fatigue response and failure characteristics of HDPE joints. The study was limited to two joining techniques: electro-fusion (E/F) and butt-fusion (B/F). Bending fatigue life and fracture behavior are presented and compared with the basic unwelded straight pipe. The influence of the joining method on tensile response and fatigue life is compared in a study of the mechanical behavior of HDPE. All specimens were subjected to four-point cyclic bending, with and without rated pressure.

2. Material and Test Specimens

The materials chosen for the pipe conformed to specifications in ASTM code (Driscopipe 1000 PE3408; Phillips Driscopipe Inc., Richardson, TX) (Ref 10) with a standard dimension ratio (SDR) of diameter-to-thickness ratio of eleven. The pressure rat-

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ing of the pipe is 1.1 MPa (160 psi). This pressure rating is obtained from the pipe thin-walled relation:

$$P = 2SF/(\text{SDR} - 1) \quad \text{(Eq 1)}$$

where S is the allowable hoop stress (800 psi), F is the environmental factor ($F = 1$ for air), and SDR is the standard dimension ratio (Ref 11).

Both the B/F and E/F pipes were made by welding two half-pieces of the plain pipe. The length of all pipe specimens was 1270 mm (50.0 in.) between the supports. The pipes were 50 mm schedule 40, having an outside diameter of 60 mm (2.375 in.) and an inside diameter of 48 mm (1.875 in.). The E/F pipe samples were provided as a gift by the manufacturer. Details of the E/F process are considered proprietary by the manufacturer. The general procedure included abrading the outer diameter of the pipe, plugging the ends of the pipe into an E/F coupler, and concurrent induction heating of the pipe, which helped fuse the coupler to the pipe wall.

Tensile test specimens were machined from the nonwelded plain polyethylene pipe (PE) pile, B/F joined pipe, and E/F joined pipe. The tensile test specimens were 6.25 mm (0.25 in.) thick with a gage section that measured 36 mm (1.5 in.) in length by 6.25 mm (0.25 in.) width. The test specimens conformed to specifications in the ASTM standard for plastic materials (Ref 10). The specimens were deformed to failure in uniaxial tension in controlled laboratory air environment (relative humidity of 55% and ambient temperature of 27 °C) at a constant cross-head speed of 50 mm/min (2 in./min).

3. Experimental Procedures

3.1 *Measurement Instrumentation*

Due to the difficulty associated with adhering sensitive measuring devices, such as strain gages to the surface of the PE pipes under conditions of large scale deformation, attempts were made to measure the bending strain using general purpose electric resistance strain gages. However, due to the large strains associated with deformation, a record of the bending strains was made during the initial cycles for small deformation levels. The strain gages were glued to the B/F and E/F joined pipes at the top surface of the specimens both at and near the joint and the unwelded plain pipe at its center. Extrapolation was made to high stress levels to estimate the actual strain during fatigue testing. Measurements up to 70% of the maximum strain were made with the aid of the strain gages. To facilitate firm bonding of the strain gages to the PE pipe, the surface of the pipe was prepared by roughening using silicon carbide impregnated emery paper. An epoxy cement (M-Bond 200) was used to glue the strain gages to the outer surface of the pipe. Cyclic strain data from the mounted strain gages were collected by a Labtech notebook data acquisition system and stored on an IBM 386 personal computer. Up to 40 cycles were effectively measured with this type of bonding.

Table 1 Tensile properties of high-density polyethylene pipes

Joining technique	Modulus, MPa	Tensile strength, MPa	Elongation to failure, %
Plain unwelded	308	23	2.46
Butt-fusion	227	22.0	2.24
Electro-fusion	158	20.0	0.70

Results are mean value based on triplicate tests.

The PE pipes were deformed with and without the rated internal pressure of 1.1 MPa (160 psi). Prior to installing each PE pipe specimen on the test apparatus, the specimen was filled with water and subsequently pressurized to 1.1 MPa (160 psi) by pumping hydraulic oil into the pipe. Indication of failure was ascertained through a water leak. Two aluminum plugs with "O" rings were used to effectively seal the ends of the PE pipe. For the nonpressurized pipes, cracks indicative of failure were visually observed. An important factor that emerged from using this test for polymeric materials is that hysteresis dissipation, arising as a result of visco-elastic nature, results in the generation of heat in a volume of material subjected to oscillating stresses. As a consequence, the cyclic bending fatigue results obtained from the thermoplastics are frequency dependent, and it is possible for the temperature to rise to the vicinity of the glass transition temperature causing the occurrence of failure as a direct result of melting and coalescence of the microscopic voids, pores, and other heterogeneities. This type of failure culminating from the conjoint action of heat (rise in local temperature) and stress is termed thermal fatigue. In an attempt to restrict the occurrence of thermal fatigue, all tests were conducted at a constant frequency of 1/16 Hz. However, the effect of frequency on failure of the pressurized and nonpressurized polyethylene pipes was not examined.

3.2 *Failure Damage Analysis*

Transverse sections of the fracture region were taken from the deformed and failed specimens. Sections were carefully prepared for examination in a scanning electron microscope (SEM). Using a sputter coater (ISI-5400), the fracture surfaces were sputtered with gold-palladium prior to examination in the microscope. The samples were examined at both low and high magnifications to reveal the region of fracture initiation, microscopic features on the surface, and fracture surface microplasticity (ductility).

4. Results and Discussion

4.1 *Tensile Response*

Table 1 summarizes the axial tensile test results. Results are the mean values based on three tests. Figure 1 compares the engineering stress-strain curves for the three pipes. As seen from these curves, the elastic modulus of the electro-fusion joined pipe specimens is similar to the plain unwelded counterpart. The stiffness or modulus of the E/F joined pipe is less than that of the B/F joined counterpart. The ultimate tensile stress shows a similar trend with the strength of the B/F joined counterpart. The ultimate tensile stress shows a similar trend with the strength of the B/F joined pipe being slightly less than that of the plain pipe and the strength of the E/F joined pipe having the lowest value. Also, the strain-to-failure (ε_f) of the E/F joined pipe was about one-half that of the B/F and the plain unwelded counterpart.

Figures 2-4 show failure of the pipe specimens. For test specimens of the plain unwelded pipe necking, failure occurred at different locations along the gage section (Fig. 2).

Table 2 Fatigue test results of 2 in. high-density polyethylene piping systems

Specimen No.	Cycles	Pressure, psi	Displacement, in.	Force, lb.	Strain, μin./in.	Stress, psi	Crack location
PEP1	29,817	160	4.5	250	20649	2204	Run out
PEP2	30,115	160	4.5	256	20649	2257	Run out
PEP3	160,547	0	4.8	295	21964	2601	On the edge of the center yoke
PEP4	172,395	0	4.5	252	20649	2222	On the edge of the center yoke
PEE1	3,813	0	4.8	275	21964	2424	End of the fused joint
PEE2	4,710	0	4.8	270	21964	2380	End of the fused joint
PEE3	5,263	160	4.8	310	21964	2733	End of the fused joint
PEE4	5,106	160	4.8	318	21964	2804	End of the fused joint
PEE5	7,989	0	4.0	227	18456	2001	End of the fused joint
PEE6	7,594	160	4.0	272	18456	2398	End of the fused joint
PEE7	10,010	0	3.5	215	16264	1895	End of the fused joint
PEE8	19,553	0	3.0	200	14071	1763	End of the fused joint
PEB1	35,090	0	3.5	228	16264	2010	Run out
PEB2	29,183	0	4.8	277	21964	2442	Toe of the butt weld
PEB3	10,987	0	4.5	260	20649	2292	Toe of the butt weld

Note: 1 psi, 6890 pascal; 1 in., 25.4 mm; 1 pound, 4.45 N

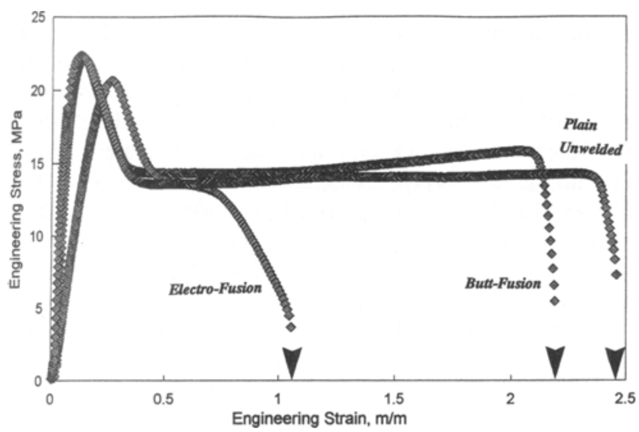


Fig. 1 Comparison of the engineering stress-engineering strain response of the fusion joined pipes with the unwelded plain counterpart

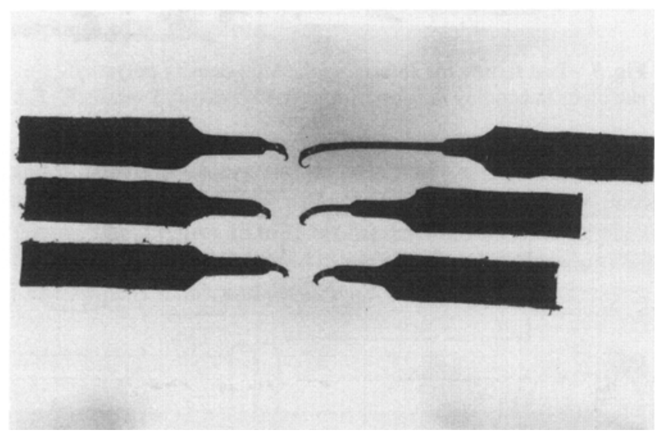


Fig. 2 Failure locations for the tensile test specimens of the plain unwelded pipe

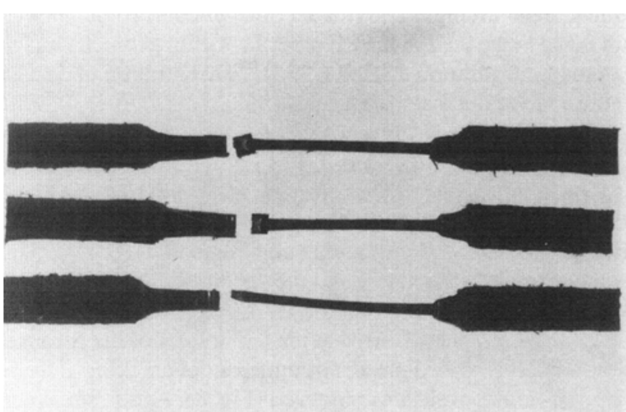


Fig. 3 Failure locations for the tensile specimens of the butt-fusion joined pipe

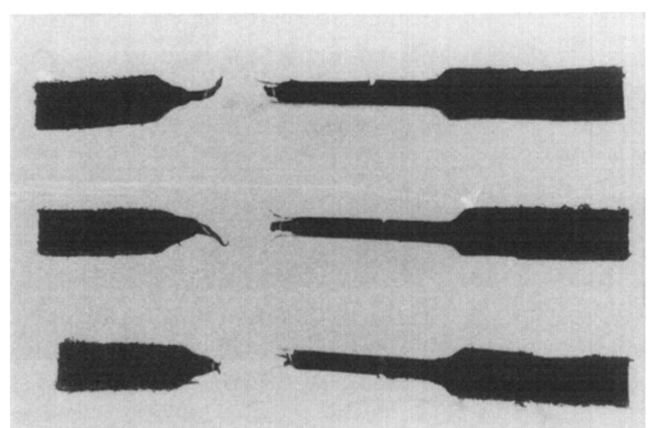


Fig. 4 Failure location for the tensile specimens of the electro-fusion joined pipes

Failure of the B/F joined specimens almost always occurred at the fusion zone (Fig. 3). Macroscopic and microscopic observations revealed features reminiscent of local ductile failure. Failure of the E/F joined specimens occurred at the location of the fusion joint (Fig. 4). Failure of this specimen revealed distinct similarity to the plain unwelded counterpart. The conformity suggests a similarity in the yield strength (σ_{ys}) and elongation-to-failure (ε_f) of the E/F and the plain unwelded test specimens, with only a marginal difference in ultimate tensile strength (σ_{UTS}). The stress-strain response of the E/F specimen is distinctly different. The yield strength, ultimate tensile strength, and elongation-to-failure are inferior to the B/F and plain unwelded counterpart. Table 2 summarizes failure locations of all specimens.

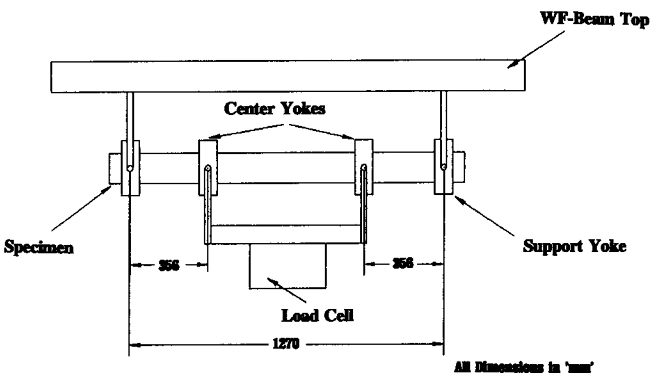
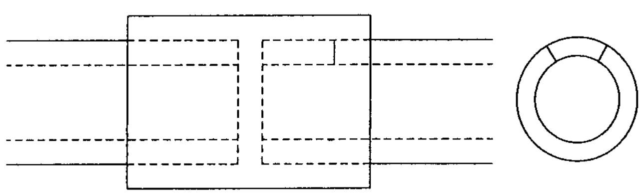
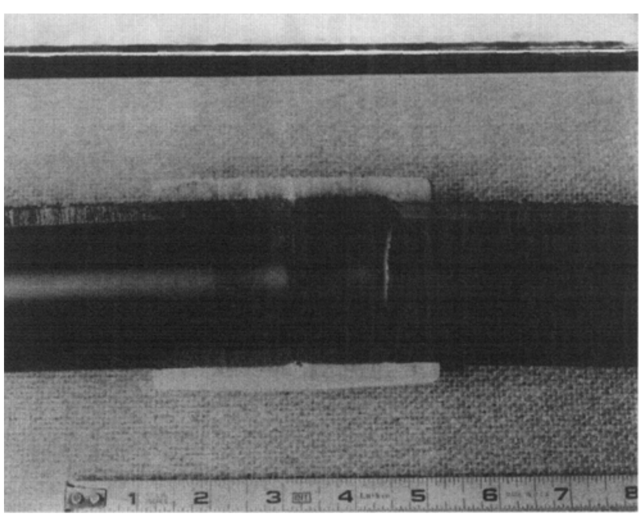


Fig. 5 Test fixture for deforming the high-density polyethylene pipes in bending fatigue



(a)



(b)

Fig. 6 (a) Schematic showing the failure location for the electro-fusion joined pipe. (b) Actual failure location for the electro-fusion joined pipe

The short term tensile test clearly reveals that specimens prepared from the B/F and plain unwelded pipe are similar and superior to the E/F joined pipe.

4.2 *Fatigue Behavior*

A total of fifteen pipe specimens were tested in a four-point bending apparatus. Figure 5 shows the test specimen fixture. The test parameters were as follows:

- Three of the specimens were B/F joined pipes.
- Eight specimens were E/F joined pipes.
- Four of the samples were unwelded plain PE pipes.

Table 2 summarizes the results. Cyclic bending fatigue testing was controlled by specifying the peak amplitude of the hydraulic actuator. The actuator amplitudes used to cycle the pipe specimens varied from +76 mm (3.0 in.) to +122 mm (4.8 in.) (Fig. 5).

The first four E/F joined PE pipe specimens were deformed at the maximum actuator amplitude of 122 mm (4.8 in.) in an attempt to ensure that these specimens would fail in a reasonable amount of time. Two of the four specimens (designated as PEE1 and PEE2) were pressurized to 1.1 MPa (160 psi), while the other two specimens (designated PEE3 and PEE4) were deformed without pressure. In accordance with expectations, the specimens deformed under identical conditions failed after a near-identical number of fatigue cycles. The bending fatigue life of the pressurized PE pipe specimens was greater than that of the unpressurized pipe specimens in spite of the existence of static axial and hoop stresses, in addition to the cyclic bending stress in the wall of the pipe. A similar trend was observed for the pressurized pipe specimen (designated PEE6) and the specimen with no pressure (designated PEE5).

For the E/F joined pipes, failure was localized at the edge of the fusion joint (Fig. 6a, b). The failure mode for this type of pipe specimen was consistent with the joint characteristics. As shown in Fig. 7, two pieces of HDPE pipe were joined by an E/F coupler with a thicker wall than that of the pipe and thus, a larger section modulus. This design assures that failure will be located on either piece of the joined pipes rather than on the coupler itself. Only the central section of the coupler was joined to the PE pipe. The end-sections of the E/F coupler were not fused to the wall of the PE pipe. This joint geometry and resultant configuration caused a stress concentration to develop at the edge of the fused area.

Three B/F joined PE pipes were deformed at displacement amplitudes of 89 mm (3.5 in.), 114 mm (4.5 in.), and 122 mm (4.8 in.). For the specimen deformed at 89 mm (3.5 in.) amplitude, the test was stopped after 35,090 cycles. The test specimen deformed at a displacement amplitude of 114 mm (4.5 in.) failed after 28,183 cycles, and the specimen subjected to 122 mm (4.8 in.) amplitude failed after 10,987 cycles. Failure for all three specimens occurred at the B/F joint. For the deformed and failed B/F joined pipes, circumferential cracking at the region of the butt-weld was observed (Fig. 8). Again, stress concentration occurs in this region. For the pipe specimen subjected to 112 mm (4.8 in.) actuator amplitude, the cracks initiated at the outer weld bead on the pipe bore (Fig. 9) and propagated through the heat-affected zone (HAZ) and onto the internal weld bead notch prior to catastrophic failure. The cracks traversed completely through the HAZ. However, there was little or no tendency for the crack to move along either the boundary of the HAZ or the center of the B/F joint. For one specimen, which failed earlier than expected, the circumferential cracks initiated at the notch on the inner weld bead and propagated rapidly through the pipe wall adjacent to the HAZ rather than traversing through it.

For the plain unwelded PE pipes, assuming these to be relatively defect free, the fatigue life was significantly enhanced. Due to the limited fatigue test data on plain PE pipes in published literature (Ref 11-15), the tests were run continuously for four to five weeks at a time prior to failure of the pipe specimens. Two of the plain unwelded PE pipe specimens were successfully deformed to failure without an internal pressure.

Figure 10 shows the results obtained from the bending fatigue tests and the variation of stress amplitude with fatigue life. Table 2 summarizes fatigue loads and the resulting bending stresses. Considering the stiffening effect of the E/F coupler, the intrinsic forces associated with fatigue testing of the E/F specimens exceeded those of the B/F specimens and the plain PE pipe counterpart. Therefore, stress amplitude-fatigue life is the most meaningful interpretation. Results shown in Fig. 10 suggest that the worst B/F joint specimen is superior to the best E/F joined specimen. In general, for a given level of stress, an approximate factor of two to three orders of magnitude difference in cycles-to-failure (N_f) was observed between the E/F and B/F joined specimens. The unwelded plain PE pipe specimens had a fatigue life approximately five times superior to the B/F joined specimens and an order of magnitude better than the E/F joined specimen.

Figure 11 shows that the results obtained in this study agree well with other research (Ref 16-19). It is apparent that at identical stress amplitudes, the unwelded plain and joined HDPE pipes used in this study show improved bending fatigue life over those obtained in earlier studies. The reason for this notable difference is rationalized on the basis that the earlier investigations were conducted at a test temperature of 80 °C. This temperature is above the α-transition temperature (70 °C) for HDPE, where the crystallized region is softer. Based on the results obtained in this experimental study, it is clear that temperatures higher than ambient temperature degrade bending fatigue durability, quantified in terms of fatigue life (N_f) of the HDPE pipe by a factor of 100 to 1000, while concurrently reducing the stress level by a factor of three to seven (Ref 20). Converting the results obtained in this study from room temperature (28 °C) to 80 °C (Fig. 12), the current test data agree well with data proposed by others. This fact clearly establishes the four-point bending test initiated and implemented in this experimental study as a potentially viable, cost effective, and time saving fatigue test technique for quantifying the fatigue response of HDPE pipes.

4.3 *Failure Characteristics*

Samples for SEM observation were cut from fully deformed and failed HDPE pipes and prepared for observation by sputtering the crack surfaces with gold prior to examination in the microscope. Figures 13 to 15 are representative micrographs of the unpressurized E/F joined pipe (PEE5), the pressurized E/F joined pipe (PEE6), and the B/F joined pipe (PEE3).

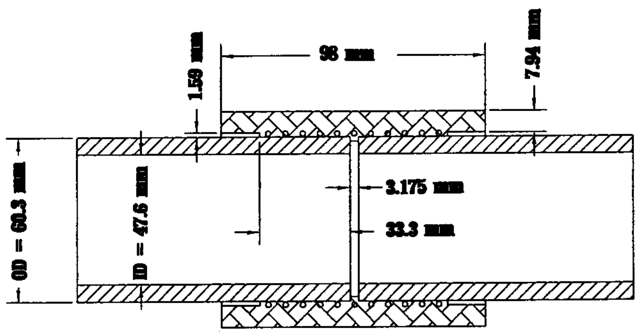


Fig. 7 Schematic showing layout of the electro-fusion joint

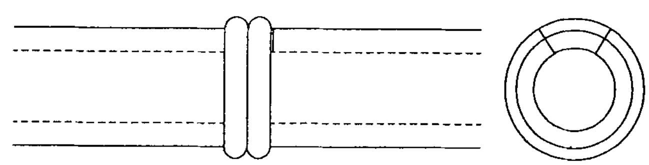


Fig. 8 Schematic showing failure location of the butt-fusion joined pipe

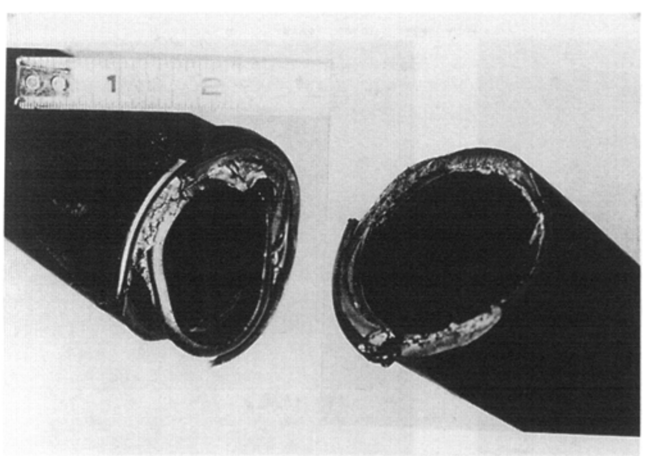


Fig. 9 Actual failure morphology of the butt-fusion joined pipe

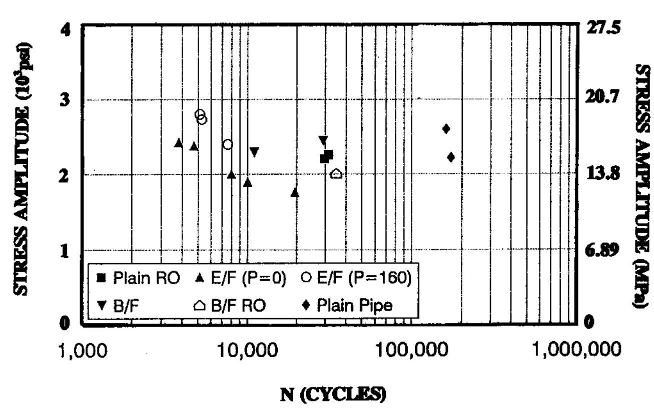
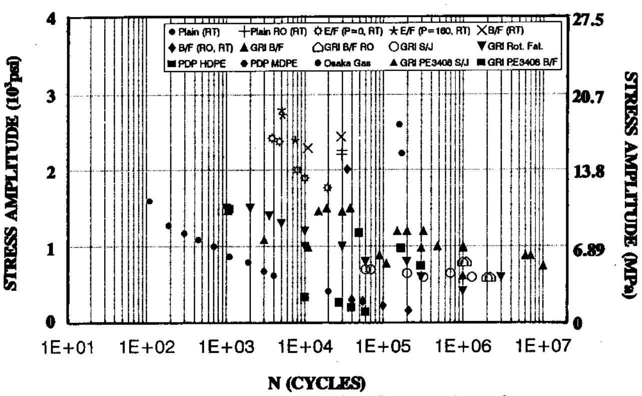


Fig. 10 Variation of stress amplitude with fatigue cycles for the high-density polyethylene pipes

Figure 13(a) is an overall view showing the failure surface (transverse section of the crack) of the unpressurized E/F joined pipe. This micrograph reveals the presence of distinct striationlike features at and near the outer surface of the failed pipe. These striations were long and regularly spaced, while those at and near the inner surface were short and irregularly spaced. Also, the striations at and near the outer surface were parallel with the plane of the pipe surface. Figure 13(b) and (c) show the outer and inner surfaces of the failed E/F pipe. The outer surface also revealed the presence of many short and irregularly spaced striations positioned perpendicular to the pipe surface. The distinct lines on the fracture surface, which were orthogonal to the propagation of the crack, were the end result of an arrested crack front. During the early stages of crack propagation, the outer surface was macroscopically flat with many arrest lines (features indicative of brittle failure). The arrest lines and the associated propagation bands display a structure similar to the other arrest lines and bands. High magnification observations revealed the macroscopically flat propagation band to be microscopically rough. However, the surface of the band becomes progressively smooth. The change in microscopic fracture surface features is repetitive in each propagation band. The distinct difference between the bands is an increased band width coupled with orientation relative to the pipe surface. Continued propagation of the crack resulted in a rough fracture surface. The transition in fracture surface topography is indicative of a change in microscopic fracture mechanism from ductile to brittle. The inner fracture surface revealed short and irregular striations on the face and pipe threads at the fringes. The threads were a result of the pipe being torn at the end of the failure process.

Figure 14 shows the overall view of the failure surface of the pressurized 1.1 MPa (160 psi) E/F joined pipe. The striations on the fracture surface were much shorter and less regularly spaced than those on the fracture surface of the unpressurized pipe. Furthermore, there was no evidence of arrest lines. While the striations on the outer surface were long and regularly spaced (Fig. 14b), the striations on the inner surface (Fig. 14c) were short and unevenly spaced. The striations on the edge of the inner surface appeared perpendicular to the pipe surface plane. In addition, many small threads were observed at the edge of the inner surface. This feature was also observed for the unpressurized pipe and is believed to occur when the last section of the pipe is torn prior to complete failure. Furthermore,



RO is Test Runout; RT is Room Temperature; All Other Data at 80 degree C.

Fig. 11 A comparative representation of fatigue test data on polyethylene pipes showing the variation of stress amplitude with cycles

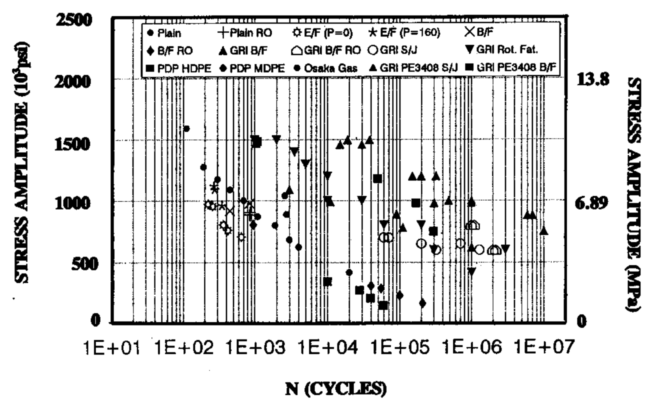


Fig. 12 A comparison of stress amplitude with fatigue cycles for all test data on polyethylene pipes at 80 °C

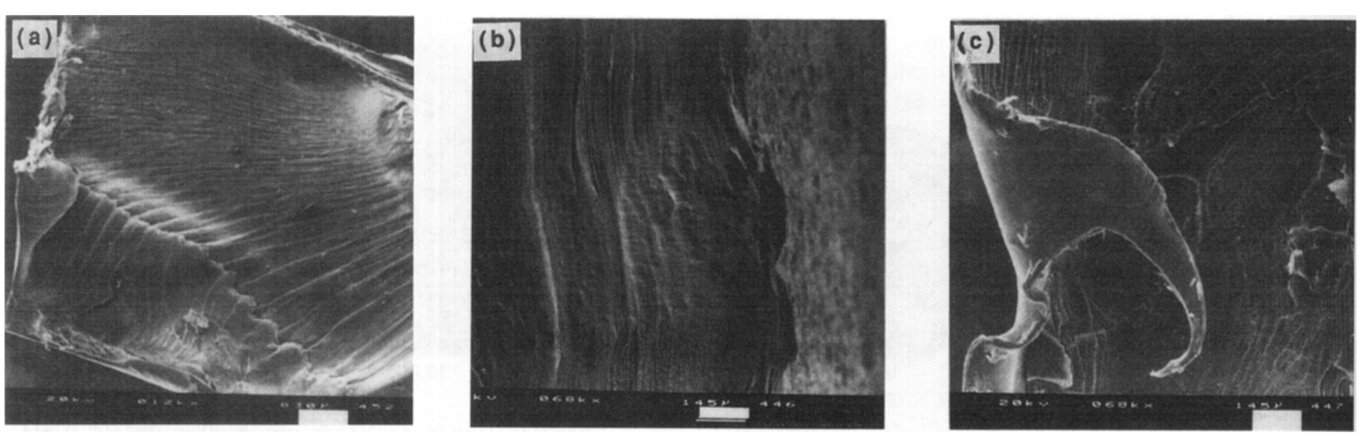


Fig. 13 Scanning electron micrographs of the deformed and failed unpressurized electro-fusion (E/F) joined pipe showing (a) an overall morphology of the failure surface, (b) the outer surface, and (c) the inner surface

the striations on the fracture surface of the pressurized pipe were shorter and less regularly spaced than those on the surface of the unpressurized pipe.

The difference in both number and spacing of the striations is attributed to the fact that for the unpressurized pipe, there is only bending stress acting on the wall of the pipe. While for the pressurized pipe, static hoop and radial stresses exist in the pipe with the external bending stresses, which are superimposed onto the static axial stress. Internal pressure in the pipes tends to decrease the plastic bending strain (Ref 14) and thus, increase bending fatigue resistance quantified in terms of cycles to failure. Additional study is planned for the near future to substantiate and/or validate the observed trend.

Figure 15(a) shows an overall view of the fracture surface of the B/F joined pipe. The crack originated at the outer surface and progressively propagated inward. Figures 15(b) and (c) show the outer and inner surfaces of the fracture and confirm the observation. The striations on the surface were long with a higher density at and near the outer surface than on the inner surface. The longest striations were near the origin of the crack, with their length decreasing as the crack propagated inward. However, unlike the E/F joined pipes, the striations at the edge of the inner surface (near the region of the butt-weld) were long and regularly spaced. During the butt-welding sequence, the material at and near the root of the joint undergoes microstructural transformation. The intrinsic material properties in this region are different from those of the substrate material. Thus, near the B/F bead, a second-phase of fatigue failure that resembles the first failure but is much shorter exists. The microstructural changes result in the presence of voids, microscopic pores, and other heterogeneities. Butt-fusion mechanics assumes that under the influence of an external load, an engineering component will fail as a direct result of the "weakest link" theory. Because the presence of material defects increases the probability of "weakest links," the section of pipe near the butt-joint reveals less strength and fatigue durability than the plain unwelded pipe material. Under bending fatigue testing, the B/F joined pipe failed after considerably fewer cycles in comparison with the plain unwelded pipe.

5. Conclusions

The following observations are based on a study of the influence of joining on the fatigue and fracture behavior of HDPE:

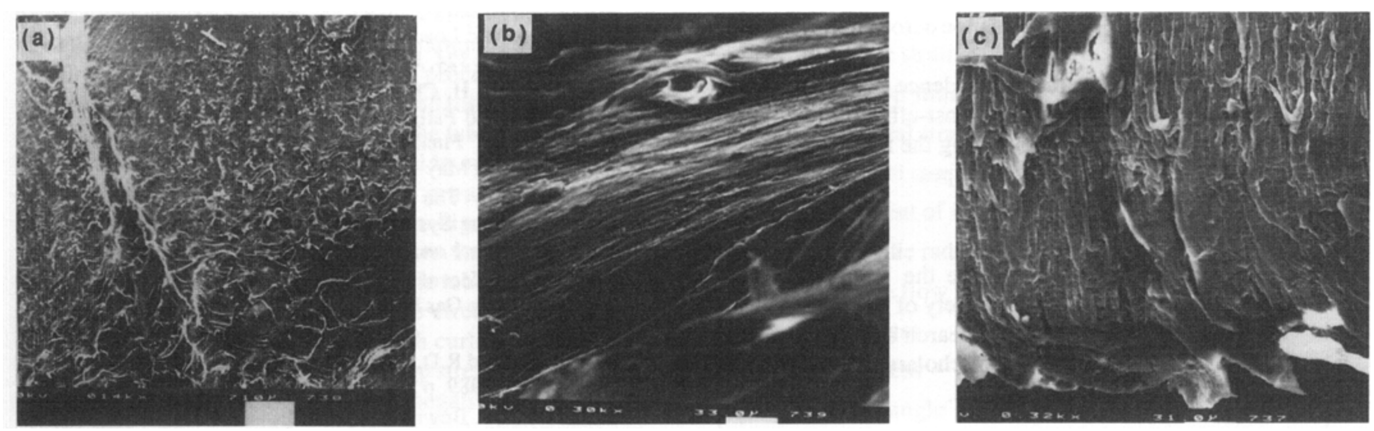


Fig. 14 Scanning electron micrographs of the deformed and failed pressurized electro-fusion joined pipe showing (a) overall morphology of the failure surface, (b) the outer surface, and (c) the inner surface

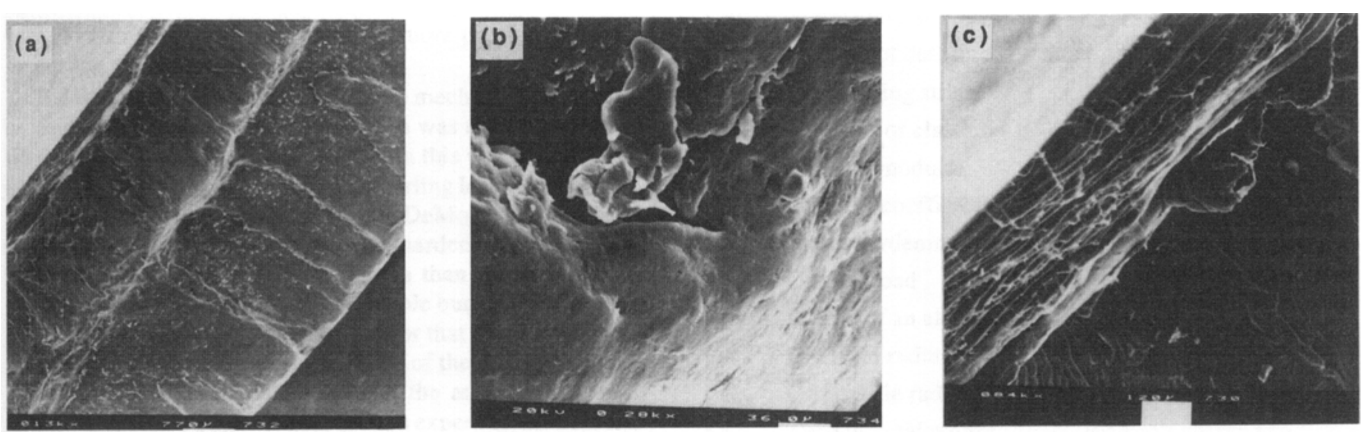


Fig. 15 Scanning electron micrographs of the deformed and failed pressurized butt-fusion joined pipe showing (a) overall morphology of the surface, (b) high magnification of the outer surface, and (c) the inner surface region

- The yield strength, ultimate tensile strength, and elongation-to-failure of the E/F joined pipes are inferior to those of the B/F joined and the plain unwelded counterparts.
- Tensile failure of the B/F joined pipe specimens occurred at the fusion zone, while tensile failure of the E/F joined specimen occurred at the fusion joint.
- The measured forces, for a given actuator displacement, associated with fatigue testing of the E/F joint specimen exceeded those of the B/F joined specimen and the plain polyethylene pipe counterpart and are attributed to the stiffening effect of the E/F coupler.
- The bending fatigue resistance of the B/F joined pipe specimen was superior to the E/F joined counterpart. At a given bending stress amplitude, the difference in fatigue life was a factor of approximately two. The unwelded plain PE pipe specimens had a fatigue life five times greater than that of the B/F joined specimens.
- Failure surface of the fully deformed and failed pipes revealed long and regularly spaced striations at the outer surface, while those at and near the inner surface were short and irregularly spaced.
- The difference in both the number and spacing of the striationlike features on the failure surface of the pressurized and unpressurized pipes is attributed to the mutually interactive influences of stresses acting on the wall of the pipe and the influence of net stress on pipe deformability and response.
- This study provided convincing evidence of the four-point bend test as a potentially viable, cost-effective, and time saving test technique for quantifying the fatigue and fracture resistance of high density PE pipes.

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