

Assessment of NDE Methods on Inspection of HDPE Butt Fusion Piping Joints for Lack of Fusion with Validation from Mechanical Testing

S.L. Crawford, S.R. Doctor, A.D. Cinson, M.W. Watts, T.L. Moran, M.T. Anderson
Pacific Northwest National Laboratory¹, USA

ABSTRACT

Studies at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, are being conducted to evaluate nondestructive examinations (NDE) coupled with mechanical testing of butt fusion joints in high-density polyethylene (HDPE) pipe for assessing lack of fusion. The work provides information to the Nuclear Regulatory Commission (NRC) on the effectiveness of volumetric inspection techniques of HDPE butt fusion joints in Section III, Division 1, Class 3, buried piping systems in nuclear power plants. This paper describes results from preliminary assessments using ultrasonic and microwave nondestructive techniques and mechanical testing with the high-speed tensile impact test and the side-bend test for determining joint integrity.

A series of butt joints were fabricated in 3408, 12-in. IPS DR-11 HDPE material by varying the fusion parameters to create good joints and joints containing a range of lack-of-fusion conditions. Six of these butt joints were volumetrically examined with time-of-flight diffraction (TOFD), phased-array (PA) ultrasound, and the Evisive microwave system. The outer-diameter weld beads were removed for the microwave inspection. In two of the four pipes, both the outer and inner weld beads were removed and the pipe joints re-evaluated. The pipes were sectioned and the joints destructively evaluated with the side-bend test by cutting portions of the fusion joint into slices that were planed and bent. The last step in this limited study will be to correlate the fusion parameters, nondestructive, and destructive evaluation results to validate the effectiveness of what each NDE technology detects and what each does not detect. The results of the correlation will be used in identifying any future work that is needed.

INTRODUCTION

The industry is pursuing ASME Code Case N-755 entitled "Use of Polyethylene (PE) Plastic Pipe for Section III, Division 1, Construction and Section XI Repair/Replacement Activities" that contains the requirements for nuclear power plant applications of HDPE. This Code Case requires that inspections be performed after the fusion joint is made by visually examining the bead that is formed and conducting a pressure test of the joint. In general, these tests are only effective if gross through-wall flaws exist in the fusion joint. The NRC wants to know whether an effective volumetric inspection can be conducted on the fusion joint that will reliably detect lack-of-fusion conditions that may be produced during joint fusing and has requested that PNNL conduct the experimental studies needed.

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MATERIALS

A series of heat-fused, butt-welded joints in 12-in. (30.5-cm) IPS DR-11, 3408 pipe material was supplied by James Craig at McElroy Manufacturing, Inc. Six fusion conditions as listed in Table 1 were provided with four joints made for each condition. The first five conditions were expected to produce a LOF in the joints and the sixth condition represented the ASTM F2620 Procedure [1] with expectations of producing a good joint.

Table 1 - Butt weld fusion conditions

Fusion Condition	Description
1	Fusion pressure during heat cycle
2	Fusion pressure during heat cycle plus 20 sec open/close
3	Fusion pressure during heat cycle plus 10 sec open/close
4	Long open/close time only (20 sec)
5	Grease in joint area – print line area after heating
6	Good joint fused with 75 psi interfacial pressure and 425°F heater surface temperature

NON-DESTRUCTIVE EVALUATION

The entire set of pipe joints was evaluated with the ultrasonic TOFD technique and by visual testing (VT). A subset of the pipes was further evaluated with ultrasonic PA and microwave technologies.

Visual Testing

Each of the outer-diameter (OD) weld beads was examined for pitting or other anomalies in the v-groove as well as mis-shaped beads. Detected small holes in the v-groove were documented. Additionally, profiles were acquired from the 24 pipe joints at 8 equally spaced circumferential positions or every 45 degrees. The left and right weld bead widths, total width, and left and right bead heights were measured from these profiles. According to the ASTM Standard F2620 [1] on heat fusion joining of PE pipe, the weld bead should be rounded and uniform in size and shape on both sides and roll back to the pipe surface. The width of the beads should be approximately 2 to 2½ times the bead height. The v-groove between the beads should not be deeper than half the bead height (see Figure 1).

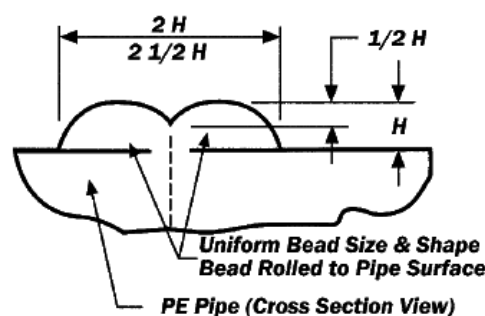


Figure 1 - Required weld bead dimensions and shape [1]

The v-groove depth was not specifically measured but cursory observations showed acceptance of the joints based on v-groove depth. Weld beads also did roll back to the pipe surface. The criterion that caused a rejection of more than half of the pipe joints was in the bead width-to-height comparisons. These values are plotted in Figure 2 for the 24 pipe joints. Data representing the 12 pipe joints that were made under the condition with fusion pressured applied during the heating cycle are on the right. All but 3 data points lie above the acceptable 2.5 bead width-to-height ratio line.

Data representing the other 12 pipe joints that were fused in the standard mode or absence of fusion pressure during the heat cycle are on the left. All of these bead width-to-height values are above the minimum acceptable 2.0 value and only 2 points fall outside the range on the high side (above 2.5) and would be rejected.

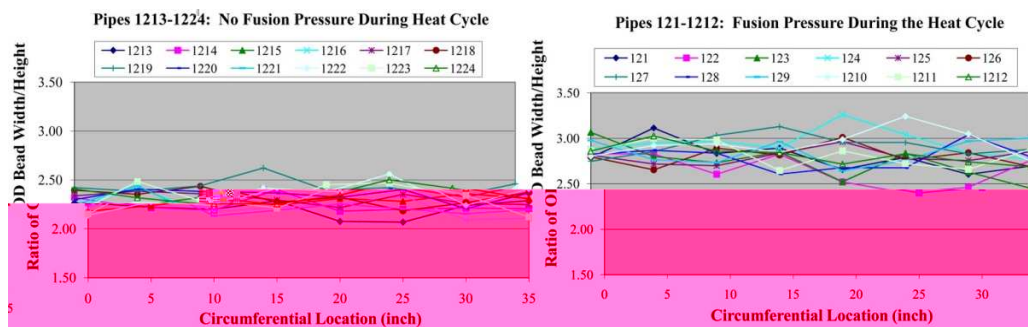


Figure 2 - Weld bead width-height values for the 24 pipe joints.
The valid range is between 2.0 and 2.5.

Ultrasonic Evaluation

Initial ultrasonic evaluations were performed with the TOFD technique. All 24 pipe joints were evaluated by NDT Innovations in partnership with Fluor while 12 of the pipe joints, 2 at each fusion condition, were examined by PNNL personnel. Later the same 12 pipe joints were evaluated with a 4-MHz integral wedge PA probe. Finally, a select 4 pipe joints at different fusion conditions were inspected with a 1.5-MHz PA probe fixed to a removable gel wedge. The gel wedge was implemented to introduce higher refracted angles in the HDPE material than a standard Rexolite wedge material would allow.

The next three figures display TOFD and PA results from the first quadrant in pipe joints 123 (top left), 127 (top right), and 1223 (bottom). These images represent approximately 10 inches (254 mm) of circumferential extent. Pipe joint 123 represents fusion pressure during the heat cycle (condition 1). Pipe joint 127 represents fusion pressure during the heat cycle and an added 20 sec open/close time before fusing (condition 2). This condition is the most severe and accordingly produces the strongest NDE flaw indications. Pipe joint 1223 represents fusion according to the accepted standard procedure (condition 6) and should produce a good joint.

TOFD data as acquired by Fluor/NDT Innovations is displayed in Figure 3. The arrows mark indications called by the inspectors. TOFD data acquired by PNNL is displayed in Figure 4. The Fluor/NDT Innovations data does not show a strong near-surface signal and is in general more sensitive to the material. PNNL data is unprocessed and acquired with commercially available probes. Figure 4 shows the flaw indications detected in pipe 127, which is the worst fusion condition of the five conditions expected to produce lack-of-fusion. A marginally suspect region was noted in pipe 1223 with the dashed line and no indications were found in pipe 123. Finally, the PA data is displayed in Figure 5. These images represent B-scan, end view images acquired at the angle specified in the image. Again, pipe joint 127 clearly shows defect responses while the other two pipe images do not exhibit flaw type responses.

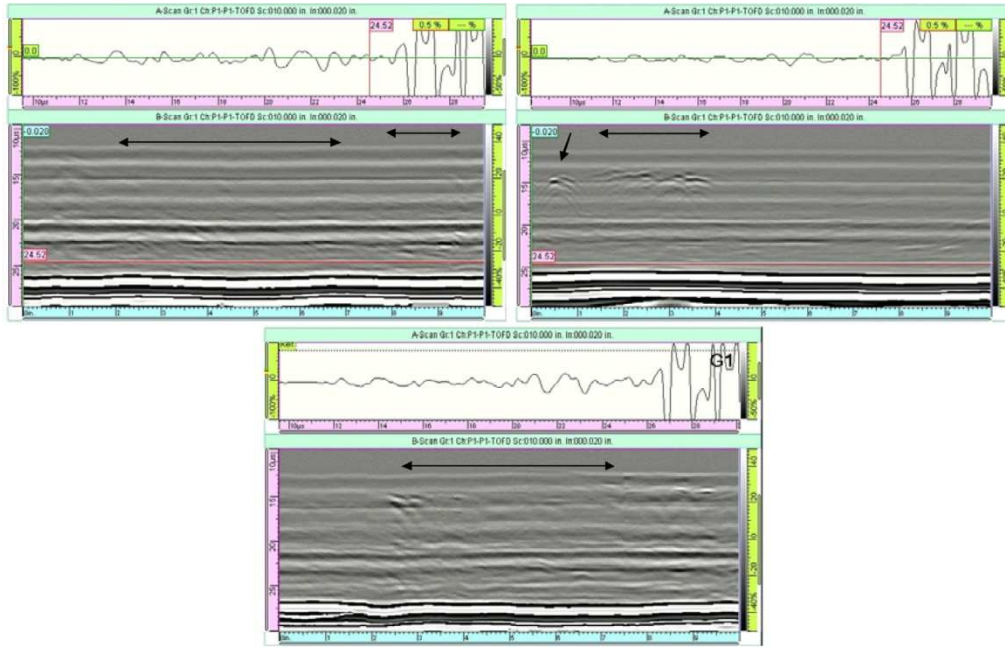


Figure 3 - TOFD data from the first quadrant of pipe joints fused under conditions 1 (top left), 2 (top right) and 6 [(ideal) bottom]. The data were acquired by Fluor/NDT Innovations.

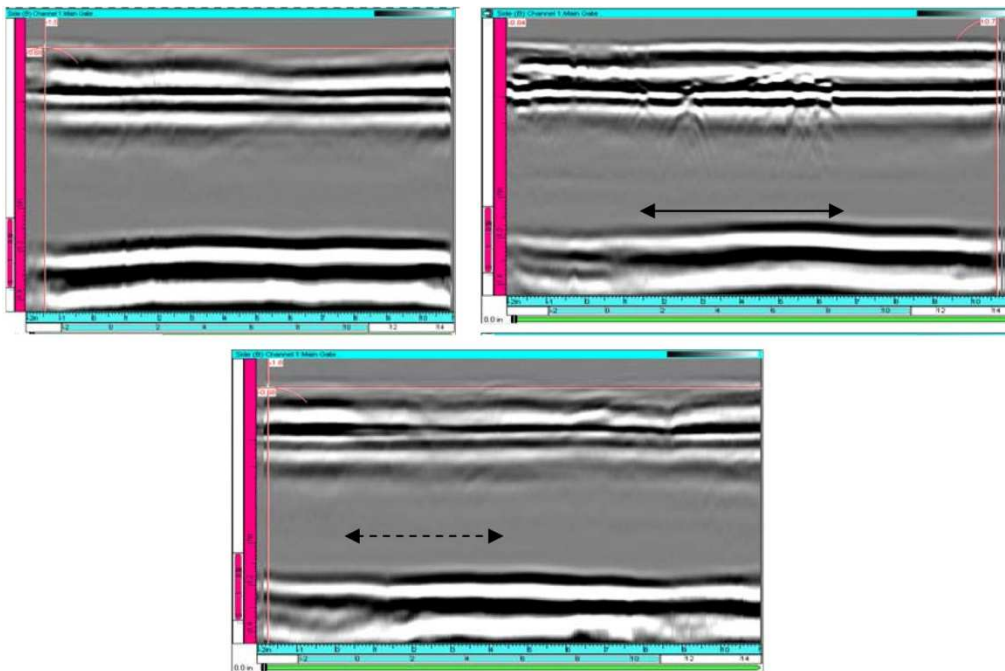


Figure 4 - TOFD data from the first quadrant of pipe joints fused under conditions 1 (top left), 2 (top right) and 6 [(ideal)bottom]. The data were acquired by PNNL.

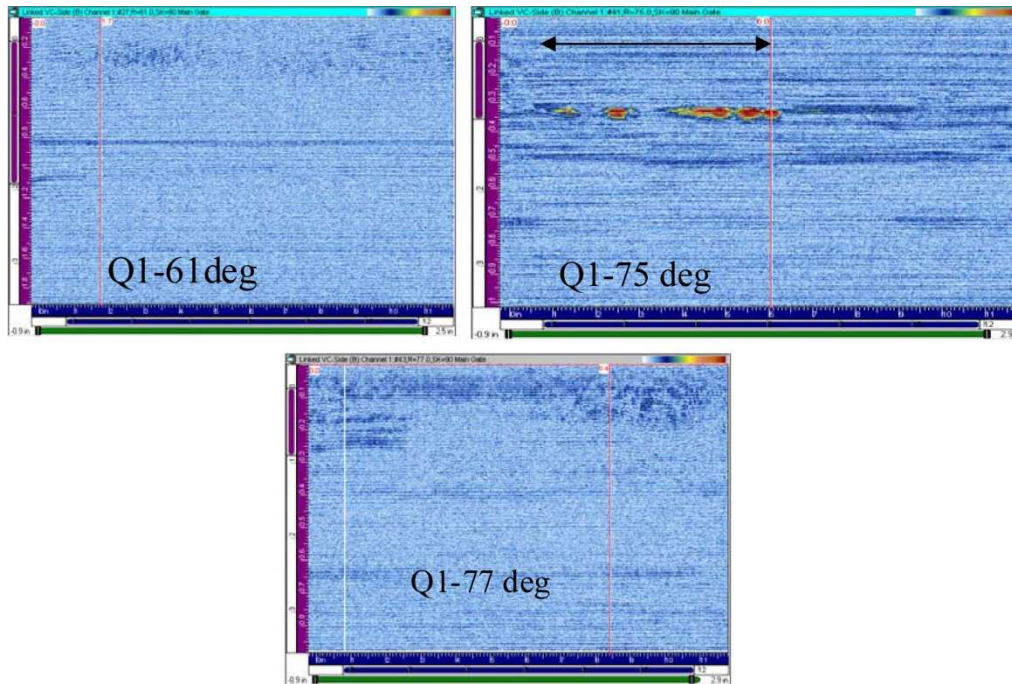


Figure 5 - Phased-array data from the first quadrant of pipe joints fused under conditions 1 (top left), 2 (top right), and 6 [(ideal) bottom]

Microwave Evaluation

The Evisive microwave technology was patented in the early 1990s primarily for the inspection of dielectric materials such as rubber and soft plastics. Delaminations, cracks, impurities, and the like cause a change in the dielectric constant of the material, which is detected and imaged as a specimen is scanned. Six of the pipe specimens, one for each fusion condition, were examined by Robert Stakenborghs at Evisive [2]. The OD weld beads were removed in order to scan the pipe joints. Data images are presented in Figure 6 for pipe joint 123, 127 and 1223. Each image represents 40 inches (1016 mm) or the full circumference of each pipe. Initially identified problem areas are circled. PNNL is still collaborating with Evisive to evaluate detection sensitivity for flaws as well as assessing base material.

NDE Data Summary

The results from all of the NDE were compiled into summary graphics to facilitate the comparison of results and to feed into the destructive evaluation (DE) to follow. The listed inspections include ultrasonic TOFD as performed by Fluor/NDT Innovations and PNNL, and PA as performed by PNNL and some limited inspections conducted by Structural Integrity. Also included are the Evisive microwave data and VT data as observed from pin holes or anomalies in the v-groove area and VT from bead profile measurements. Specimen summaries for the first quadrant of pipe joints 123, 127, and 1223 are displayed in Figure 7. Indications were found in each of the quadrants by multiple techniques. Dotted lines indicate marginal calls where there was an NDE response but not a typical flaw response. The highest occurrence of detected flaw indications is in pipe joint 127, fused under the most severe condition.

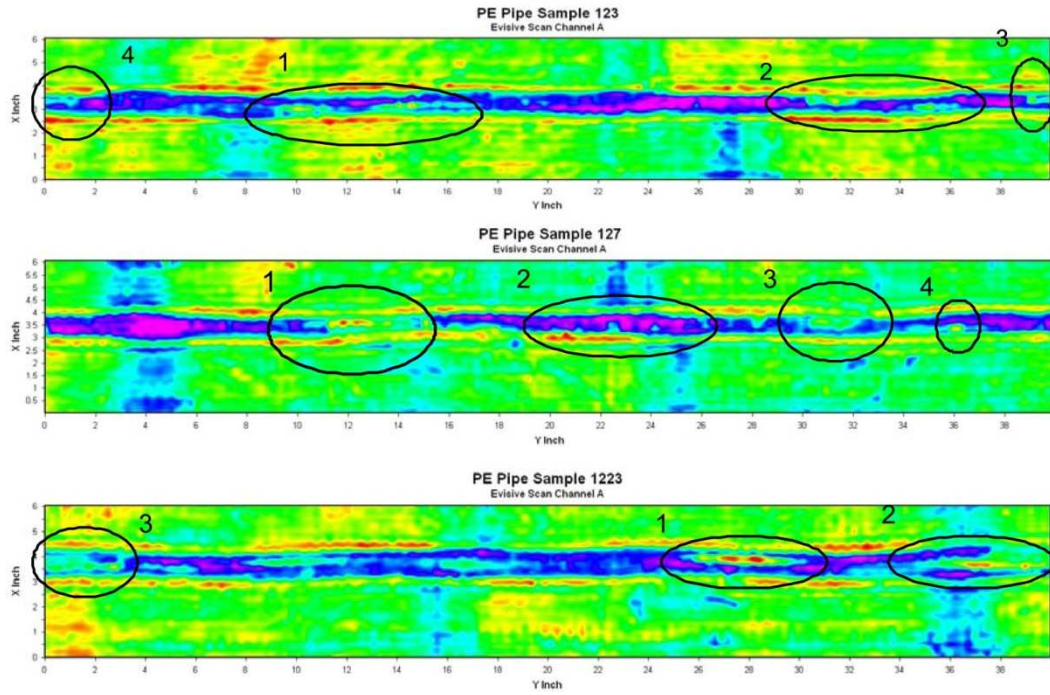


Figure 6 - Microwave data from all four quadrant of pipe joints fused under conditions 1 (top), 2 (middle) and 6 [(ideal) bottom]

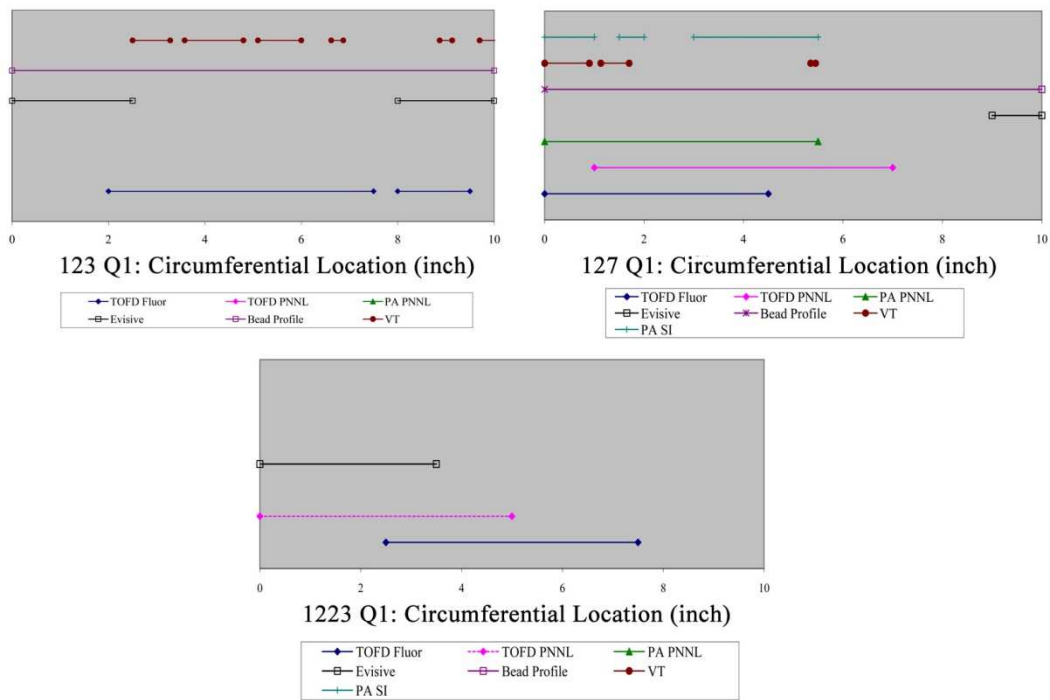


Figure 7 - Compilation of NDE flow indications for the first quadrant from pipe joints 123, 127 and 1223

DESTRUCTIVE EVALUATION

Based on the earliest ultrasonic testing, an initial six sections of three pipe joints were destructively evaluated with the high-speed tensile test. The testing was performed by James Craig at McElroy. This work has been previously reported [3] and is summarized in Table 2. The testing was surprising in that the “good” joint (1224) failed. The other two joints showed mixed results. At this point, PNNL began investigating other types of mechanical testing.

Table 2 - High speed tensile test results

Failure Mode	Failure Location	Pipe ^(a)	Fluor Call	PNNL Call
Ductile	O/S	1215	good	good
Ductile	O/S	1215	bad	good
Brittle	HAZ	126	bad	bad
Brittle	HAZ	126	good/bad	good
Brittle	HAZ	1224	good	good
Ductile	GAGE	Base		
Ductile	GAGE	Base		
Ductile	GAGE	Base		

^(a)Pipe 1215 – condition 4, Pipe 126 – condition 2, Pipe 1224 – condition 6

After further discussions and community input, PNNL was directed to the guided bend test as documented in a Plastic Pipe Institute (PPI) draft technical note. The basic guided bend test places either the pipe ID (root bend), pipe OD (face bend), or entire joint (side bend) in tension with a die and plunger arrangement. The plunger or mandrel radius of curvature is designed to be approximately two times the pipe wall thickness (or test coupon specimen thickness). With this radius, a 23% or greater strain is placed on the specimen as it is bent, which is above the lower limit in yield strain. The bend test as outlined by ISCO Industries [4] states a 38% strain is produced in the material. To prepare material for this test, the pipe was cut into 0.75 to 1 inch (19.1 to 25.4 mm) strips that were then run through a planer. Three of the tested strips are displayed in Figure 8. The left and center images are from pipe joint 1224, fused under the standard procedure. The bend test showed no failure on the left specimen, which represents the 3-inch (76.2-mm) circumferential position. A brittle failure is observed in the center image, acquired at 1-inch (25.4-mm) circumferential. A brittle failure is also noted in the right image, acquired from specimen 127, worst fusion condition, at 36-inch (914.4 mm).

Every one of the seven tested strips from pipe joint 127, worst fusion condition, failed in the brittle mode by the side-bend test. This joint was selectively tested at positions containing flaw indications and at positions without flaw indications. Each piece failed rapidly; that is, minimal plunger displacement was needed to cause failure. From this result, PNNL assumed that the entire pipe joint would similarly fail and it was not tested further. Pipe joints from the remaining five fusion conditions were subjected to the bend test over two full quadrants. The results of these bend tests were color coded for a summary presentation. Figure 9 displays the results from pipe joints 123 and 1223, fusion conditions 1 and 6, respectively. Quadrant 1 starts at the top zero mark and proceeds counter-clockwise. A green region represents no flaw, light green indicates a small flaw with both ID and OD ligament intact, yellow indicates the joint opened but had either an intact ID or OD ligament, and the red indicates a through-wall failure. The other tested joints similarly had good regions and regions that failed. PNNL is currently evaluating these findings and correlating the DE and the NDE results.



Figure 8 - Bend test results on pipe joint 1224 (standard fusion procedure), left two images, and on pipe joint 127 (worst fusion condition) on the right

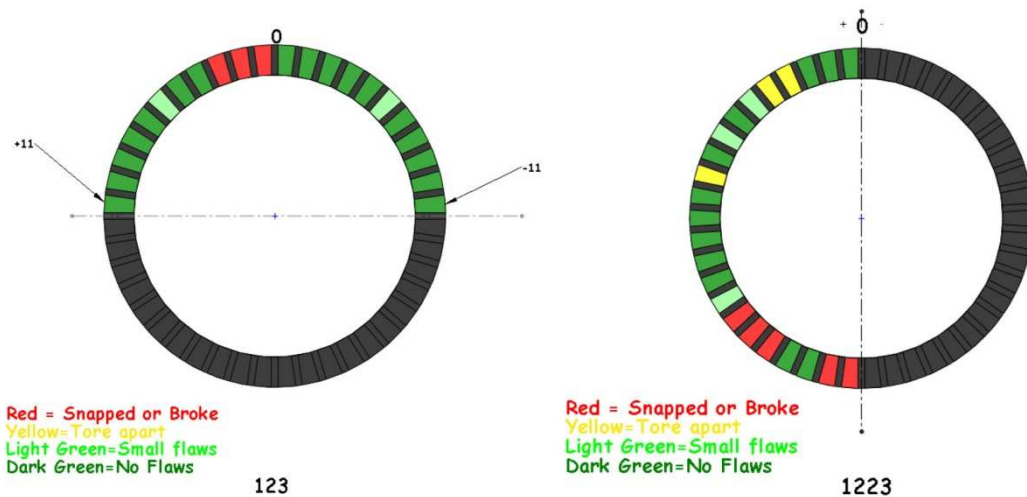


Figure 9 - Side-bend test results on pipe joints 123 and 1223

SUMMARY AND CONCLUSIONS

To evaluate the effectiveness of NDE in determining butt fusion joint integrity in HDPE piping, a series of pipe joints were fused and examined with visual, ultrasonic, and microwave testing. A visual examination was able to detect the abnormal fusion condition of applying fusion pressure during the heat cycle. Based on weld bead aspect ratio, the pipes fused under these conditions were rejected. The fusion joints were volumetrically inspected for lack of fusion with ultrasonic and microwave technologies. The worst-case fusion condition produced flaw indications that were clearly found in the ultrasonic evaluations. Flaw indications were found in all fusion conditions, even the standard condition. Some of the areas identified as flawed and some as non-flawed from three fusion conditions were evaluated with the high-speed tensile test. The results were mixed in that some areas identified as non-flawed failed in the tensile test. This led to further evaluations with the bend test. Of the six pipe joints tested, one for each condition, no joint was fully acceptable. These results are being evaluated and correlated to the NDE findings. However, because of time, an inadequate analysis has been conducted to date to be able to make any statement about the effectiveness of the ultrasonic or microwave technique on the six HDPE specimens being studied. This data analysis will be performed in the near future.

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- [2] R. Stakenborghs, J. Little, “Microwave based NDE inspection of HDPE pipe fusions,” presented at the Proceedings of the 17th International Conference on Nuclear Engineering 2009, ICONE17, Brussels, Belgium, July 12–16, 2009.
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- [4] S. McGraff, A. McElyen, “Side bend testing on pipe weld samples using testing fixture w/ hand hydraulic pump,” ISCO Industries, 2009.