

Ultrasonic Technology Applied to Polyethylene Pipe Butt-Fusion Joints Uses, Limits, Acceptance Criteria

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Abstract

Understanding the polyethylene butt fusion joint structure is important when using Non-Destructive Examination (NDE) technologies to examine for flaws, discontinuities, tolerable defects, and critical defects. PAUT and TOFD and MICROWAVE are accepted non-destructive examination methods used on HDPE pipe and fusion joints, each with its own benefits. Each can detect voids and inclusions, under controlled environmental conditions. Field implementation requires adjustment versus controlled conditions, in order to obtain clear calibrated readings. While certain implemented technologies are portrayed in as proprietary, some general guidelines exist for acceptance criteria, which parallel the guidance from ASME BPVC Section XI.

Introduction:

HDPE pipe butt-fusion joints can be inspected by Visual Examination, Ultrasonic Examination, Microwave Examination, X-Ray Examination. Statistically, virtually all process-compliant butt-fusion joints are clean and clear, passing NDE. A very small number of joints, formed under adverse conditions, may present flaws. ASME BPVC Section XI is working to establish flaw criticality criteria to assign criteria, beyond which a tolerable “flaw” transitions into an un-acceptable “defect”.

In the USA, since 1960 (just under 60 years ago), for polyethylene pipe diameters ranging from 2-inch to 24-inch, an estimated 180,000,000 fusion joints have been made and buried in-service. The fact that only a very small, tiny, fractional percentage of all butt-fusion joints have ever failed is a great testimony to the simplicity and reliability of the polyethylene materials and fusion procedures implemented over the last 6 decades. Today’s technology, which uses ASTM F3124 data-recording to verify fusion process compliance with ASTM F2620 fusion procedures, has further improved reliability, when additionally

validated according to ASTM 3183 (Guided Side Bend Test). All fusions performed within the standardized ASTM F2620 processes are “Fusions”. All butt-joints formed outside of the standard parameters are rejected as “Non-Fusions”. The elusive term of “Cold-Fusion” occurs outside of the boundary F2620 fusion parameters, and hence are “non-fusions” and are removed because they do not comply with the proscribed data-record temperature-pressure-time plot. However, today, owners want an additional, simple NDE record verifying fusion joint integrity, because, the NDE technology exists. More importantly, general collective NDE acceptance criteria should be established as a starting point, subject to additional evolution. This paper proposes base-line multi-acceptance-criteria, subject to evolution with additional research and round-robin collective optimization and validation.

Discussion:

Plastic Pipe Institute **Technical Note 51** outlines the terminology and structural formation of the butt fusion joint. The actual “joint” is the 25-micron to 50-micron thick co-crystallization interface between the previous two pipe butt-ends. Figure 4 in this document gives a good illustration of the butt fusion joint internal structure. The task of all calibrated NDE technologies is to assess the quality of this planar 0.001-inch to 0.002-inch thickness. The remainder of the polyethylene melt-flow forming fusion beads, are indicators of the properly formed, interior, interfacial, inter-digitized, molecular-diffusion, co-crystallized “joint”. (A thorough reading of PPI TN-51 is recommended.)

<https://plasticpipe.org/pdf/tn-51-fusion-joint-formation-structure.pdf>



Current and emerging NDE technologies for HDPE butt-fusion joints are :

**** UltraSonic Testing (UT)**

- phased array ultrasonic testing (PA-UT)
- time-of flight diffraction (TOFD-UT)

**** Microwave Testing (MT)**

**** X-Ray Testing (XT)**

Each of the above NDE technologies can detect voids, inclusions, flaws, or anomalies. Numerous organizations (e.g. code bodies, standards bodies, inspection companies and users) are actively developing and evaluating the instrumented NDE techniques for plastic pipe and butt-fusion joints. Several ASTM NDE Standards have recently published, providing guidance on equipment and hardware. Typically, with UT technology, the ultrasonic transmitter and receiver must be “shaped” to the diameter of the pipe being examined and calibrated for the material and pipe wall thickness. Considerable pre-testing and calibration is required prior to hardware field use. (Microwave is a non-contact NDE technique based on the material dielectric; the hardware is used is the same for most diameter ranges.) Additionally, UT depends on constant sonic velocity through the material being examined. The sonic velocity through polyethylene is dramatically affected by temperature variance, such that while it works easily in the controlled laboratory environment, in the field there are issues remaining “in calibration”, because the temperature variance from the under belly of the pipe

to the top crown of the pipe can be 50°F or more, in the heat of the summer. More than one UT project has had to conduct testing in the dark at midnight to 6 am, to avoid thermal calibration problems.

Several NDE companies can demonstrate high detectability of known flaws that are detrimental to butt-fusion joints. Further work is required to assure an accurate, quality examination. Improvements are indicated to improve the probability of detection (POD) and to reduce the false call rates (FCR; false positives).

NDE inspector qualification and experience in plastic pipe fusion NDE is critical to assure high quality results. Users should ensure that NDE Inspectors (Level I, Level II, Level III) have adequate training and experience with plastic fusion joint inspection procedures when selecting an NDE service provider. Qualifications of those conducting the inspection could include the requirements listed in the applicable standards of practices or technical specifications, such as:

- ASNT Practice SNT-TC-1A Personnel Qualification Certification
- ANSI/ASNT-CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel
- NAS 410 Certification and Qualification of Nondestructive Testing Personnel2
- ISO 9712 Non-Destructive Testing—Qualification and Certification of NDT Personnel

Currently, neither the NDE industry nor the polyethylene pipe industry offer standardized acceptance criteria. Determining mutual acceptance criteria prior to on-site NDE inspection is of utmost importance. Minimal guidance on indications, flaws and defects is given in ASTM E1316-18a Standard Terminology for Nondestructive Examinations Section A. “Indications”, or irregularities, found during the non-destructive examination process need to be verified as flaws. When usually tolerable flaws create excessive stress risers, the “flaws” are re-classified as intolerable “defects”. Defects are quantified by their detrimental effect on expected service life. The accept-reject criteria from any technology should be based on the quantification of any indication as a tolerable flaw or intolerable defect, using validated, peer reviewed criteria.

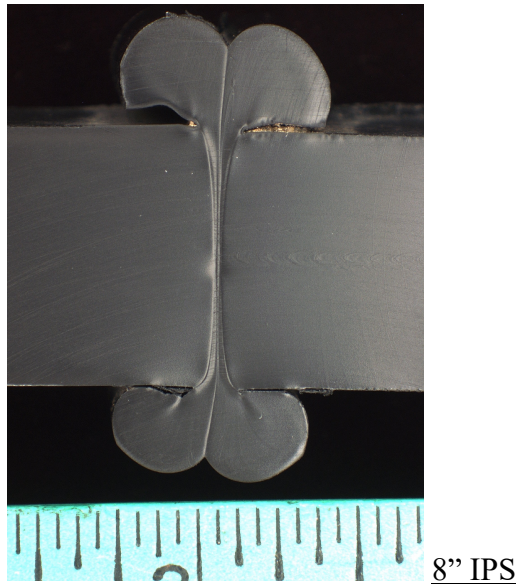
Starting Proposal for Acceptance Multi-Criteria:

To this end, multi-acceptance criteria are proposed for PE4710 and PE100 resins with PENT>2000-hours. Most flaws are interpreted individually. However, multiple flaws can become a composite defect if the composite impact reduces service life because of increased local stress intensity. The primary assumption is that the tolerable local stress intensity is less than the LTHS, with a design factor applied. When PE4710 pipe is pressurized to its working pressure rating at 73°F (23°C), the circumferential stress is 1000-psi, and the axial tension is 500-psi. Butt-fusion joints, subjected to 500-psi axial tension, are at 50% of the HDS of the PE4710 pipe grade material. Hence, butt-fusion joints endure a long time. When local stress risers force the stress intensity above the HDS, near to or above the LTHS, the service life can be compromised.

A. Remnant Wall Ligament: For simplicity, the stress through the polyethylene pipe wall is assumed to be uniform. However, it is slightly non-uniform, being slightly higher than the nominal value on the ID and slightly lower on the OD. Hence, defects nearer the ID have slightly more negative impact than near the OD. The typical legacy OD scratch tolerance is to allow an axial or diagonal OD scratch depth up to 10% of the minimum wall thickness. This is mitigated by the fact that most HDPE can be 3% to 6% overweight (over-wall); however, the 90% ligament rule remains, even when the wall is minimum wall thickness. With a 10% scratch depth, the adjacent local axial stress is intensified to at least 111%, moving from 500-psi to 555-psi, still well below tolerable stress limits. Assume that the gouge tip stress intensification has a k-value of 2.5; the local 555-psi could intensify to 1388-psi. Still acceptable. So, how deep of a gouge would be tolerable to not exceed 1600-psi LTHS? $1600/2.5 = 625\text{-psi}$. $625\text{-psi} / 500\text{-psi} = 1.25$ $1.0 / 1.25 = 0.80$. Hence, with regard to axial stress, a minimum

remnant wall ligament that is 80% of the initial wall thickness could be the absolute lower limit wall ligament thickness. The same axial gouge would act to increase circumferential stress. Assuming a tolerable long term stress of nominally 1160-psi, a remnant wall thickness of 86% would locally transform the ordinary 1000-psi hoop-stress to $(1.0 / 0.85 = 1.16)$ 1162-psi. As a locally tolerable stress value for 4th generation PE100 and PE4710 bimodal pipe grade polyethylene materials, possessing PENT values >2000-hours, it is suggested the industry should consider, evaluate, and test a lower limit for remnant pipe-wall ligament thickness of no less than 85%, for combined surface gouging and wall interior flaws.

B. Butt-fusion Facial Area: With proper OD and wall alignment, the butt-fusion wall area gets increased by about 20% to 25% through the fusion flow-zone, as the melt radially flows in tension to form the increased bead OD, and in compression, flows to decrease the ID bead diameter. Across the width of the melt-Flow-Zone (MFZ), the “vee” of the fusion joint usually is above the surface of the pipe, on both the OD and ID. By measuring the width of the pipe wall from the OD-vee to the ID-vee, and by using the Vee-OD diameter and the inner-bead Vee-ID diameter, one can calculate the actual fusion interfacial area, and compare it to the pipe’s actual butt-end wall area. Detailed calculations show that the interfacial fusion zone wall area is increased. Hence, the axial stress across the fusion interface is lower than the adjacent axial stress in the pipe wall area. Hence, in axial tension, the fusion joint is “slightly stronger than the pipe wall”, because it has larger mass and enlarged cross-sectional area.



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On this basis alone the fusion joint interfacial area might be reduced by defects amounting to nominally 20% without suffering a shortened service life. Additionally, the PE4710 fusion interface can tolerate an area reduction because it is subjected to only 500-psi, ordinarily.

Due to radial flow of “melt-puddle” on the butt-end of the pipe, as it forms the melt-flow-zone, most flaws and defects are squashed flat and stretched thin, forming worst-case flat planar defects. Their stress intensification k-factor may be a worst- case $k=2.5$. With the fusion bead intact, with increased fusion face area, with the pipeline operating at PE4710 WPR, the axial stress is ordinarily 500-psi at minimal wall thickness. Because the fusion joint MFZ cross-sectional area is larger, the ordinary axial stress reduces to about 416-psi, without over-wall being considered. If the tolerable area reduction is about 15%, then the peak intensified stress might be $416\text{-psi} \times 2.5 / 0.85 = 1225\text{-psi}$, a tolerable local flaw long-term stress intensity.

One method to calculate the area involved in area reduction, might be to plot the circular butt-face area, dividing it into 1000 equal-area sections. Based on the NDE finding, the number of flawed sections are marked as non-fusion points,

and subtracted from the total interfacial area. As long as the total reduction of defective area is less than 15% (150 sections vs 1000 sections), the area reduction meets the **provisional 85%** remnant interfacial-area criteria.

NOTE: Obviously, the alignment of the OD and wall area (OD concentricity and “high-low”) is very important, and in the presence of flaws, the flaws might convert into defects due to the rise in local adjacent stresses, because of the loss of interfacial fusion area. The “high-low” loss of interfacial fusion area should be deducted from the maximum fusion area in assessing the remnant facial area. The beneficial effects of proper butt-fusion OD & ID alignment cannot be understated.

NOTE: Ordinarily most defects are individual voids or inclusions. However, in dust burdened fusion areas (deserts or arid land), some fusions may exhibit multiple indications, which individually are innocuous. But together, multiple particles form a cluster of weakness whose collective diameter or area constitutes a measurable defect. When multiple indications conglomerate, and their separation distance is no more than five particle diameters apart, then the cluster might considered to be a flaw or defect whose “size” is the circumscribed diameter and area of the cluster.

Summary:

Virtually all pipe grade polyethylene butt-fusion joints are free and clear of indications, flaws, and defects. There is a tremendous record of success with butt-fusion integrity over the past 60 years, which incorporates 4 generations of polyethylene materials and improved fusion processes. Today, NDE methods have the ability to find and isolate flaws and defects, and to quantify them by number, size, and location. When those few fusions with indications are NDE examined, an assessment must be made

by trained personnel. Critical flaw analysis is a complicated field impacted by material fracture toughness and several other variables. A simplified approach is suggested for PE100 and PE4710 pipe grade resins with PENT > 2000-hours. To assess the impact of verified flaws, it is suggested that two criteria be evaluated simultaneously: remnant pipe wall ligament thickness AND remnant fusion interfacial area. The provisional flaw and defect acceptance criteria are proposed to be wall ligament thickness greater than 86% of the minimum pipe wall thickness, and simultaneously, interfacial fusion joint area greater than 86% of the minimum pipe-wall area. Starting from there, further research is indicated to determine if these baseline criteria must be narrowed, or may be broadened. Further research is indicated.

Interested parties are encouraged to join ASME BPVC, Division 1, Section XI - **Working Group on HDPE Pipe Flaw Evaluation: Detection and Assessment.** The author can provide contact information to join.

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