PIPA

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POP020

Principles of polyethylene (PE) electrofusion welding and assessment

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PRINCIPLES OF POLYETHYLENE (PE) ELECTROFUSION WELDING AND ASSESSMENT

1.0 INTRODUCTION

The purpose of this technical guideline is to provide insight into the principles of electrofusion (EF) welding and instruction on the identification and assessment of fractographic features resulting from electrofusion weld quality testing. Electrofusion weld tests are typically destructive tests, where an applied stress is used to fracture the joint or components. Evidence of a satisfactory weld is determined by assessing the modes of fracture. Fractographic features include gross ductile tearing (yielding), micro-ductility, and brittle lack of fusion and voids.

Good fusion is demonstrated by ductile yielding / tearing (gross or micro) through the plane of the EF fitting wires or ductile fracture of the pipe or fitting socket.

This industry guideline applies to EF fittings manufactured in accordance with AS/NZS 4129 *Fittings for polyethylene (PE) pipes for pressure applications* that have been fused to PE pipes manufactured in accordance with AS/NZS 4130 *Polyethylene pipes for pressure applications.*

2.0 ELECTROFUSION WELDING PROCESS

A comprehensive description of the EF welding process is provided in PIPA Industry Guideline POP001 Electrofusion Jointing of PE Pipes and Fittings for Pressure Applications. POP001 includes an overview of the training and equipment required, step-by-step instructions for common installation techniques and important considerations for effective EF jointing. Reference should be made to the guideline prior to performing EF welds.

3.0 PRINCIPLES OF ELECTROFUSION WELDING

EF welding requires application of an electric current for a defined period of time (fusion time) to resistance heating wires contained within the fitting. These wires are either embedded beneath the internal surface of the fitting (Figure 1) or exposed at the internal surface of the fitting (Figure 2).

Heat generated in the wires raises the temperature of the surrounding PE material above the crystalline melting point. At either end of the heating zone the molten PE solidifies first (in regions known as "cold zones"), creating a cavity within which the PE melt is constrained. The expanding PE creates pressure within the cavity so that fusion takes place between the pipe and fitting interfaces.

The colour indicators or fusion indicator pins on the fittings will become visible if the required pressure has been created. Once the fusion time has elapsed, the joint assembly is left to cool undisturbed for a set time (cooling time). This cooling phase is critical to ensuring good, strong joints.

Figure 1 – Inner wall of electrofusion coupler with embedded wire design.

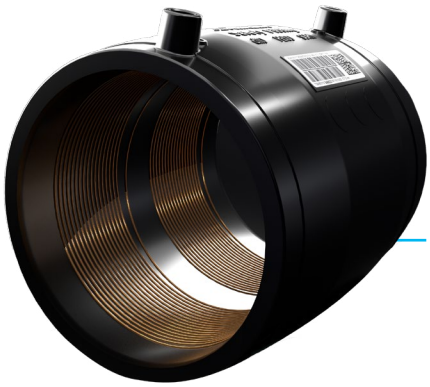

Figure 2 – Inner wall of electrofusion coupler with exposed wire design.

Image courtesy of Aliaxis

4.0 CRITICAL FACTORS FOR SUCCESSFUL FUSION

Good fusion results in high strength and ductility at the interface between the pipe and EF fitting. This forms a common over-structure, created by co-crystallisation of the macromolecules beyond the weld interface.

Critical factors for achieving good fusion are outlined in Table 1. Fusion energy, power, temperature, and time are defined by the fitting manufacturer for each size and type of fitting. Fusion times and voltage are encoded into the fittings barcode which is read by the control box. Where a portable electric generator is used, it must have suitable capacity for welding the fitting. Good fusion is also highly dependent on using appropriately calibrated and maintained equipment and following the correct procedures for joint preparation and cleanliness.

Table 1 Critical factors for achieving good fusion in addition to joint preparation

CRITICAL FACTOR	DESCRIPTION	COMMENTARY
Fusion energy and power	Energy required to melt the polymer for a specified fusion time.	Specified by the fitting manufacturer. Power supply quality is important.
Fusion temperature	Melting, polymer expansion and molecular mobility driving diffusion and molecular entanglement.	Specified by the fitting manufacturer but can be influenced by quality of the power supply and control box maintenance.
Fusion time	Development of the correct temperature profile at the joint interface to achieve the above.	Specified by the fitting manufacturer.
Fusion/melt pressure	Melt pressure across the entire interface must be achieved for diffusion to occur.	Influenced by joint preparation, cleanliness, and assembly
Cooling time	Diffusion of molecular chains creating co-crystallisation of macromolecules beyond the weld interface are locked in either side of the joint.	Critical to ensuring joint strength and ductility.

Note: For more details on these critical factors including joint preparation refer to PIPA POP001 - Electrofusion Jointing of PE Pipes and Fittings for Pressure Application

5.0 TEST METHODS FOR ASSESSING ELECTROFUSION WELDS

There are several published methods for assessing EF weld quality. The primary test method referenced in AS/NZS 4129 - *Fittings for polyethylene (PE) pipes for pressure applications* is the peel decohesion method ISO 13954 – 1997 *Plastics pipes and fittings — Peel decohesion test for polyethylene (PE) electrofusion assemblies of nominal outside diameter greater than or equal to 90 mm*. The test method has two distinct phases:

- The first involves preparation and destructive testing of the test pieces.
- The second phase is an assessment of the result. In particular, whether fitting – pipe interface fusion has been achieved across a minimum length of heating zone area.

Note: Where fracture occurs in the plane of the winding or at the fusion interface, the EF fitting side of the test piece shall be assessed for the percentage of brittle decohesion. Typically, matching fractographic features will be observed on both pipe and fittings sides of the fracture zone.

This is a destructive test method, where the test pieces are always taken to destruction. ISO 13954 (Clause 7d) requires the location of the fracture to be recorded. The four different fracture locations include - in the pipe or fitting socket, between the windings or at the fusion interface. These fracture locations are to be reported as per the requirements in Clause 9 of ISO 13954.

ISO 21751:2011 *Plastic pipes and fittings – Decohesion test of electrofusion assemblies – Strip-bend test is another test* method referenced in AS/NZS 4129 which looks at the same modes of fracture.

Test method ASTM F1055-2016 *Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene and Crosslinked Polyethylene (PEX) Pipe and Tubing* is similar to ISO 13954, although there are differences in the applied rate and direction of loading. ASTM F1055 is more explicit in describing the fracture modes than ISO 13954 and what constitutes failure of the weld. In particular, tearing between the winding is a passing result. Refer to the bullet points below:

- Ductile failure between wires is described as a Passing Result (refer to figure A2.4 of ASTM F1055).
- Ductile failure in the pipe is described as a Passing Result (refer to Figure A2.3 of ASTM F1055).
- Brittle separation of fusion zone is described as a Failing Result (refer to Figure A2.5 of ASTM F1055).

Note: The ISO 13954 test method also requires the maximum breaking load to be recorded and reported. In addition to this, it is recommended that where the tensile-testing machine has the capability to record load vs. extension, this information be kept. Load vs. extension plots can be a useful aid in fracture mode assessment.

6.0 ASSESSMENT OF FRACTURE MODES

When assessing destructive weld test coupons to ISO 13954, the location of the fracture is to be recorded in accordance with Clause 7 d), including the type of fracture (i.e., ductile or brittle). However, the current version does not explicitly state only separation at interface is considered a failure. Instead, it requires the measurement of the total maximum brittle fracture length in the fusion plane.

Tearing between the windings or fracture through the pipe or fitting wall is evidence that fusion between the interfaces has been achieved, indicating a pass result.

Typical types of fractures are as follows:

DUCTILE FRACTURE IN THE PIPE WALL

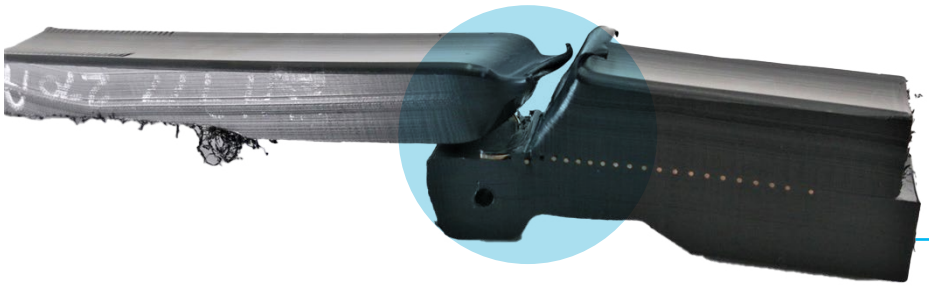

Figure 3 – shows ductile fracture of the pipe wall has occurred.
This is a Pass result.

DUCTILE FRACTURE IN THE FITTING SOCKET

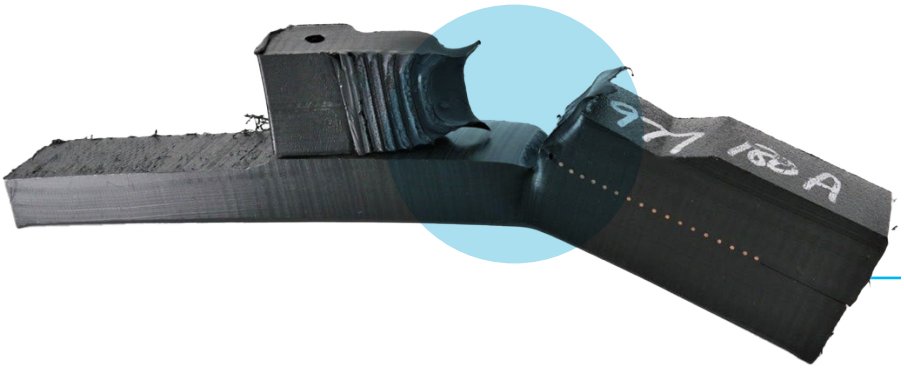

Figure 4 – Figure 4 shows partial separation through the windings, followed by ductile fracture through the fitting socket wall. **This is a Pass result.**

DUCTILE FRACTURE IN THE PLANE OF THE WINDINGS

It must be recognised that not all ductile surfaces will look the same. Nor will the fracture surface necessarily look the same across the sample width. Edge effects, slight misalignment can alter the appearance of the surface.

Where tearing between the wires occurs, it is expected that some differences in surface appearance will be apparent. The geometry of the test piece changes during the test, the stress field differs between the edge zones and the body of the test piece, strain rate will vary.

This means that the observed level of ductility can vary from obvious gross tearing of the PE material (gross ductility) to very minor tearing of the PE material known as micro-ductility. Confirmation of **micro-ductility** will require the use of low magnification light microscopy (refer to Appendix B Micro-ductility)

Tearing between the windings over a length of at least 66.7% of the fusion zone demonstrates satisfactory fusion of the PE across the interface.

Figure 5 – shows ductile fracture (tearing) of the PE between the windings. Stress whitening is apparent across most of the fusion zone surfaces, with some gross ductility near the edges towards the centre of the test piece. **This is a Pass result.**

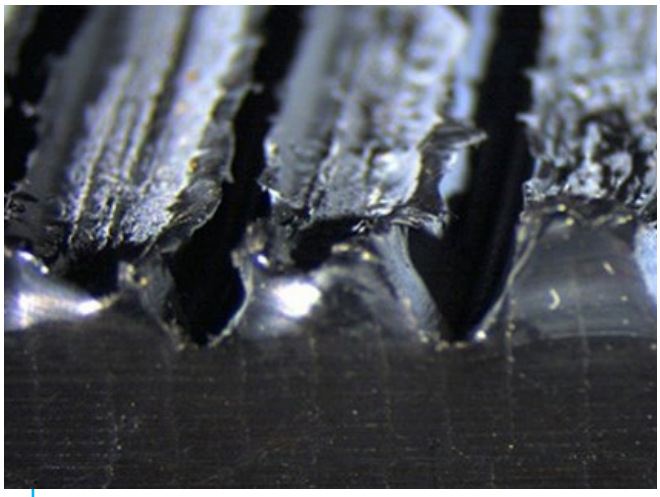

Figure 6 – shows the side view of ductile fracture with tearing of the PE occurring between the windings of the heating wire. The wires are no longer encapsulated in the PE and have been dislodged. Ductile tearing present in the fracture zone.

BRITTLE FRACTURE AT THE FUSION INTERFACE

Where separation occurs at the interface between the pipe and fitting surfaces, an assessment needs to be made as to whether there is evidence of ductility. A brittle fracture, indicating absence of fusion, will be flat and featureless. Stress whitening at the fracture surface is indicative of fusion at the interface as is gross ductility.

In accordance with AS/NZS 4129, voids are treated as regions of brittle fracture. Examples of voids are shown in Figure 13. Heating wires dislodged during destructive testing are not to be classified as voids.

Figure 7 – shows a large area of brittle separation at the interface of the pipe and fitting surfaces.
This is a Fail result.

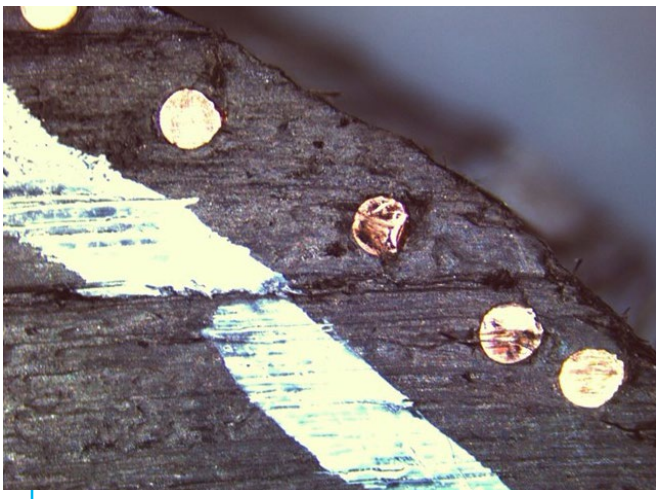

Figure 8

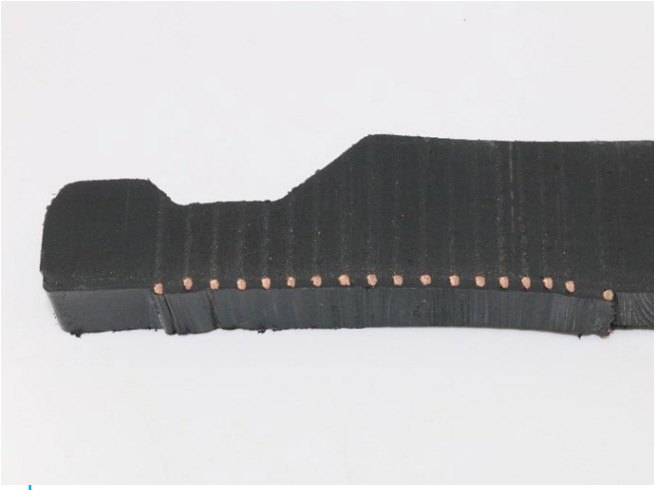

Figure 9

Figures 8 and 9 shows a side view of brittle fracture occurring at the fitting pipe interface with embedded heating wires remaining encapsulated in the PE. **Figure 9 shows a Fail result.**

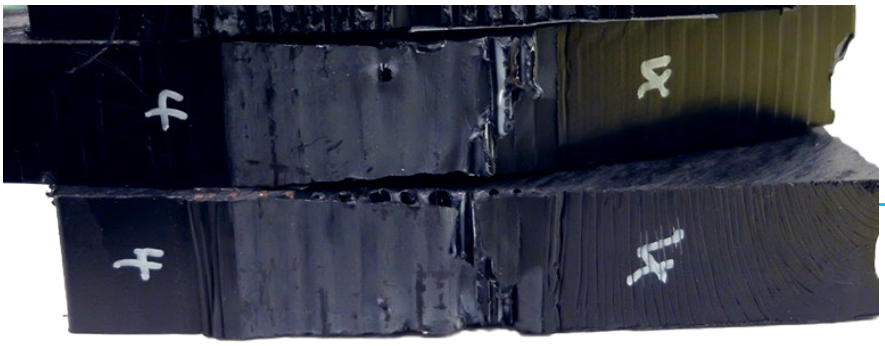

Figure 10 – shows brittle separation at the interface by the featureless surface.
This is a Fail result.

MIXED MODE FAILURES

Mixed mode failure is defined as multiple fractographic features present along the entire length of the fusion interface, i.e., ductile tearing or yielding in the plane of the wires, brittle lack of fusion and voids.

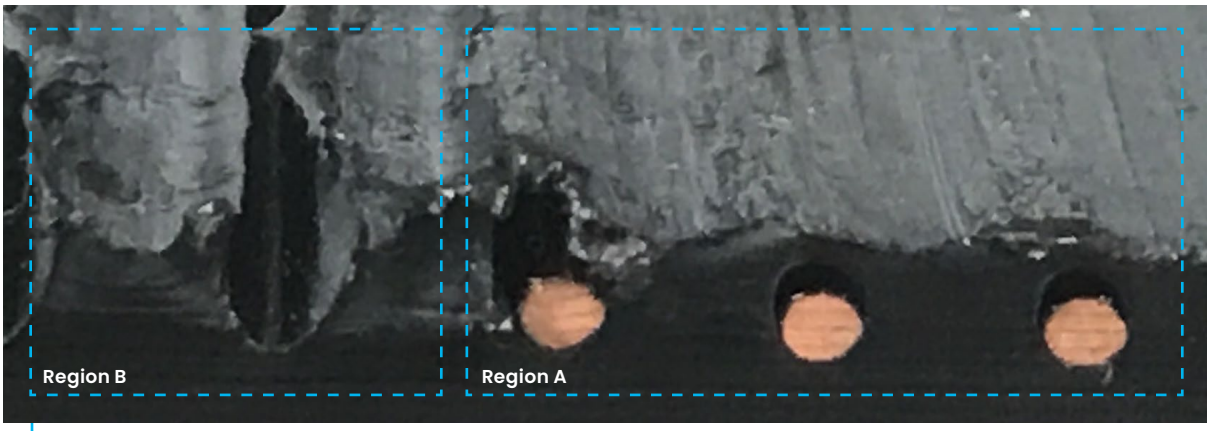

Figure 11 – is a close-up, side view of the EF fitting weld that matches the pipe side shown in Figure 12 below.

Region A: Brittle fracture in the weld interface zone between the pipe and EF coupling and above the wire plane. Some minor ductility exhibited around the 2nd and third wires from the right. No corresponding wire imprints formed on the pipe side.

Region B: Ductile yielding of the material between the wire locations.

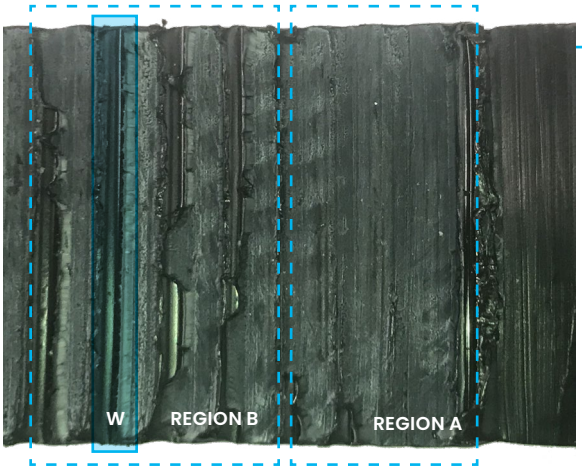

Figure 12 – is a close-up of the pipe fusion interface exhibiting mixed mode failures – ductile and brittle / lack of fusion zone.

Region A: Pipe side, essentially a featureless surface showing brittle fracture in the weld interface zone, wire imprints from the EF fitting have not formed.

Region B: Pipe side ductile yielding of the PE material between the well-defined wire imprints (W).

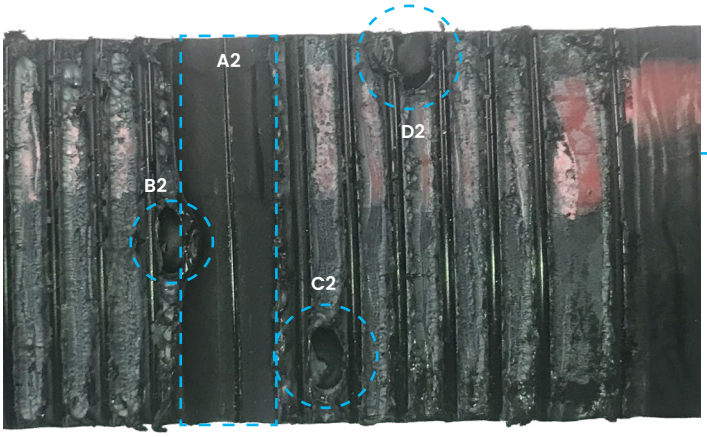

Figure 13 – shows the pipe side of an EF weld exhibiting a large void (A2) that transverses the entire width of the test sample plus three small voids (B2, C2 & D2). Remaining area exhibits ductile yielding in the plane of wires.

Section 6.1 provides a full fractographic assessment of the fracture zone and calculation of percentage brittle decohesion region for **Figure 11 & 12** and **Figure 13**.

6.1 MIXED MODE – PERCENTAGE BRITTLE DECOHESION ASSESSMENT AND CALCULATION EXAMPLES

The following calculation examples are based on figures 11 &12 and figure 13 of a peel decohesion test as per ISO 13954 on DN250 EF weld assemblies. They are evaluated in terms of their fractographic features and the resultant percentage brittle decohesion.

Mixed mode fractographic features – percentage brittle decohesion calculation

EXAMPLE 1 – ASSESSMENT FIGURES 11 & 12

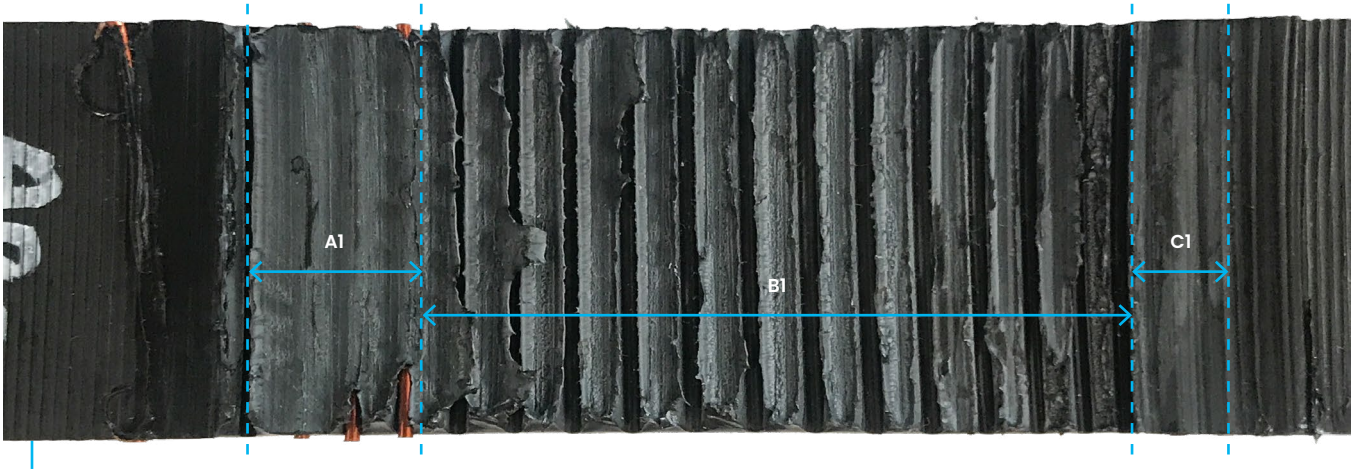

Figure E1.1: Electrofusion coupler – plan view of full fracture zone based on the close-up image shown in Figure 11.

- A1 and C1 are brittle fracture regions within the full fracture zone. These regions show a smooth featureless surface and wires remain in place and covered. Fracture in these regions is at the interface between the pipe and fitting, indicating lack of fusion.
- B1 is a ductile fracture region, with material yielding occurring through the plane of the wires.

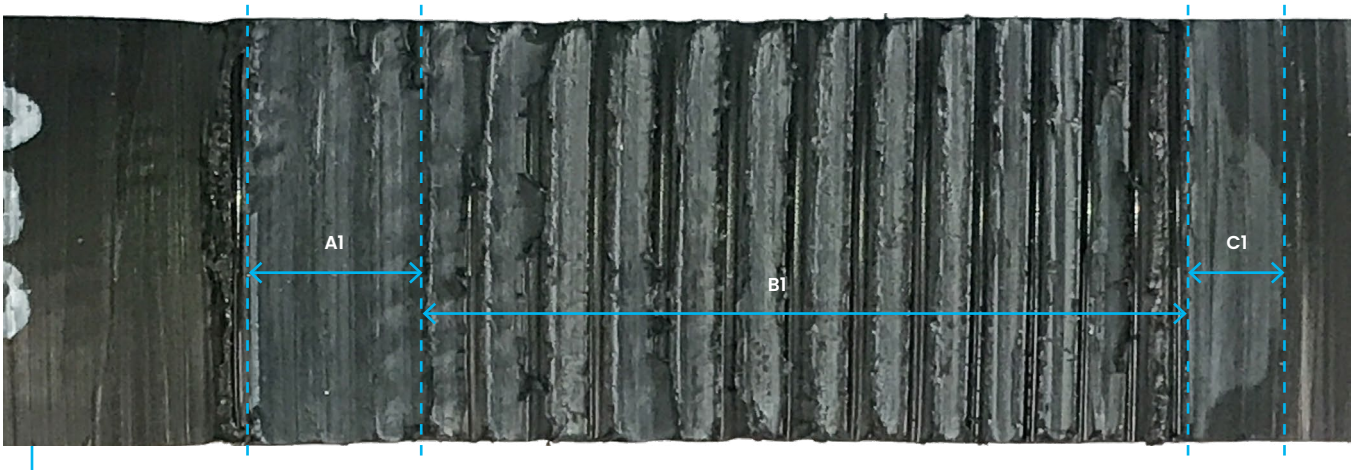

Figure E1.2: Pipe side – plan view of the full fracture zone based on the close-up image shown in Figure 12.

- A1 and C1 are brittle fracture regions within the full fracture zone. These regions show a smooth featureless surface and no wire imprints visible.
- B1 is a ductile fracture region where wire imprints are clearly visible.

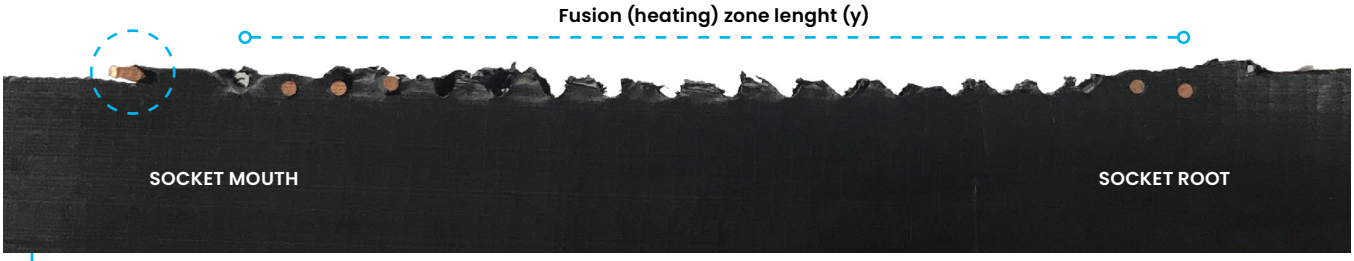

Figure E1.3: Electrofusion coupler – side view of the full fracture zone based on the close-up image shown in Figure 12.

Figure E1.3 shows the fusion heating zone length that is used in the calculation of the percentage brittle decohesion. This length should be measured prior to destructive testing and is typically defined as the length where there is even spacing between the wires. The blue circled wire is at a greater off set versus the evenly spaced wires in the heating zone. The end of the wire connects to the EF fitting terminal and does not form part of the fusion zone. In many cases the fusion zone length is specified in EF fitting manufacturers product data sheets and should be used where available.

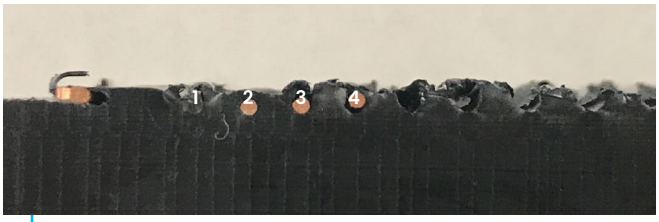

Figure E1.3.1: Close-up of EF coupler socket mouth showing brittle fracture at the fusion interface from heating wire locations 2 through to 4.

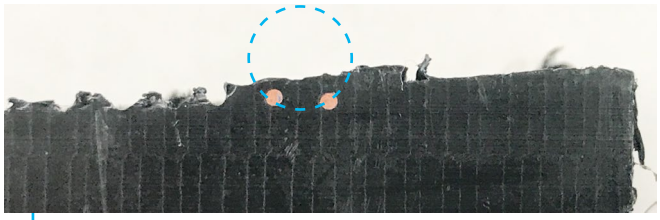

Figure E1.3.2: Close-up of EF coupler socket root showing brittle fracture at the fusion interface for the last two wires (circled above).

Calculating the percentage brittle decohesion

This calculation focuses on taking the measurements of the EF coupler side of the weld using Figures E1.2 and E1.3.

Measurements:

Fusion (heating) zone length (y) = 68.7mm
Brittle fracture length (A1) = 11mm
Brittle fracture length (C1) = 6mm

Calculations as per ISO 13954:

d2 (maximum brittle fracture length)
= (A1 + C1) = 17mm

Percentage brittle decohesion:
$CC = \frac{d2}{y} \times 100 = (17/68.7) \times 100 =$ **24.7%**

Result:

Cc = 24.7% which is < 33% brittle.
This is a pass result.

EXAMPLE 2 – TREATMENT OF VOIDS, ASSESSMENT OF FIGURE 13

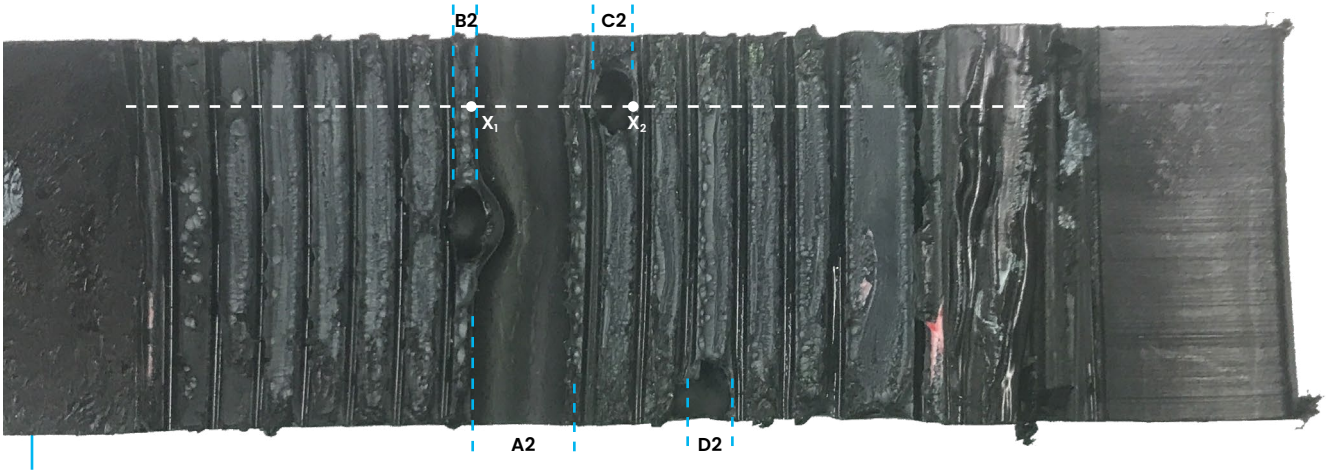

Figure E2.1: Electrofusion coupler – plan view of the full fracture zone matching the close-up image of the pipe side shown in Figure 13.

- This shows the EF coupling side with the matching large void (A2) that transverses the entire width of the test sample, plus the three smaller voids (B2, C2 & D2).
- Voids B2, C2 and D2 are equal to the width of each individual fusion region (spacing between wires). It should be noted that these spacings are not always equal. The wire location width is not to be treated as part of the void zone.
- It should not be assumed that small voids extend across the full width of the test piece.
- Only voids in the same plane shall be measured and used in the calculation of the brittle decohesion zone. This is achieved by drawing a straight line through the fracture zone that presents the worst case in terms of accumulated voids and brittle fracture, represented by the line that runs through points X_1 to X_2 in figure E2.1 above. The summation of the individual void lengths (A2 + C2) between X_1 and X_2 is the brittle fracture length.
- The remaining area exhibits ductile yielding in the plane of wires.

Note: Void treatment rationale is based on two potential failure modes in EF joints:

i) Shear strength reduction – a small void will not cause the same reduction in shear strength of a joint as a void that extends across the full width of the test piece.

ii) Leak path creation – several off-set voids will have a lesser effect on the length of the leak path in the joint than would the same number of voids extending across the full width of the test piece.

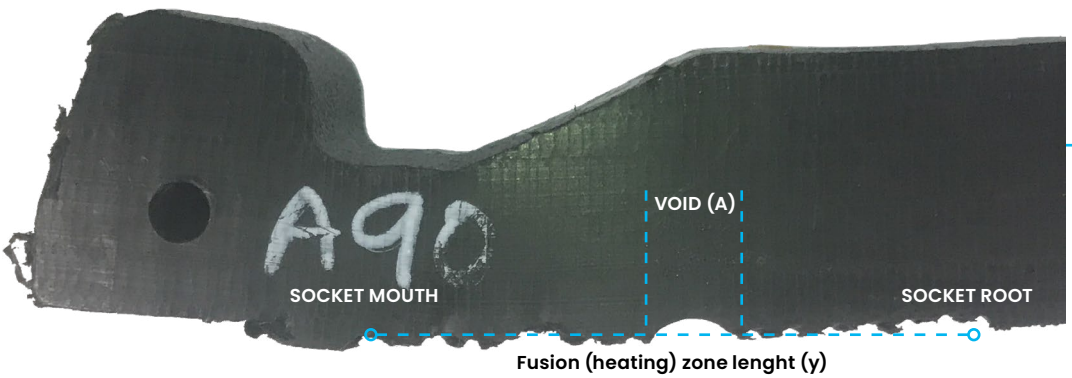

Figure E2.2: Electrofusion coupler – side view of the full fracture zone.

This shows the fusion heating zone length that is used in the calculation of the percentage brittle decohesion.

Calculating the percentage brittle decohesion

This calculation focuses on taking the measurements of the EF coupler side of the weld using Figures E2.1 and E2.2.

Measurements:

Fusion (heating) zone length (y) = 64mm
Void length (A2) = 7.5mm
Void length (B2) = 1.7mm
Void length (C2) = 2.8mm
Void length (D2) = 2.6mm

Calculations as per ISO 13954:

d2 (maximum brittle fracture length)
= (A2 + C2) = 10.3mm

Percentage brittle decohesion:
Cc = × 100 = (10.3/64) x 100 = **16.1%**

Result

Cc = 16.1% which is < 33% brittle.
This is a pass result.

7.0 TECHNICAL REFERENCES

J. Bowman, T. Medhurst and R. Portas, Procedures for the quantifying the strength of electrofusion joints, Plastics Pipes VIII, Kongingshof, The Netherlands, September 1992.

J. Bowman, Stages in the development of the strength of electrofusion joints, ANTEC 1992

J. Bowman, A review of the electrofusion joining process for polyethylene pipe systems, Poly. Eng. And Sci., Vol. 37, No. 4, p674, 1997.

J. Bowman, The assessment of the strength of electrofusion joints, Twelfth plastic fuel gas pipe symposium, Boston, 1991.

8.0 STANDARDS REFERENCES

- AS/NZS 4129:2020 *Fittings for polyethylene (PE) pipes for pressure applications*
- AS/NZS 4130 *Polyethylene pipes for pressure applications*
- ASTM F1055-2016 *Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene and Crosslinked Polyethylene (PEX) Pipe and Tubing*
- ISO 13954 - 1997 *Plastics pipes and fittings — Peel decohesion test for polyethylene (PE) electrofusion assemblies of nominal outside diameter greater than or equal to 90 mm*
- ISO 21751:2011 *Plastic pipes and fittings – Decohesion test of electrofusion assemblies – Strip-bend test*

APPENDIX A

DEFINITIONS

Term	Definition
Ductile, ductility	Fractures characterised by material tearing and plastic deformation such as stretching and elongation.
Tearing	Breaking apart a material through the application of force without the aid of a cutting tool.
Yielding	Behaviour of a material stressed beyond the elastic limit and exhibiting permanent, inelastic deformation.
Brittle	Fracture of any component with little or no macroscopically visible plastic deformation. Brittle fracture usually involves little energy absorption.
Decohesion	Separation of the pipe and fitting at the weld interface or in the plane of the electrofusion wires.
Rupture	Rupture, or ductile rupture describes the ultimate failure of ductile materials loaded in tension.
Fracture	Separation of two halves of the test specimen under the action of stress.
Failure Mode	Pattern of failure defined by distinctive features of the deformed shape after failure; manner in which the failure occurs i.e., brittle, ductile or mixed mode.
Fractography, fractographic	Analysis and characterisation of features generated on the fracture surface of a test specimen or engineering component.
Destructive test	Test method resulting in damage or destruction of the sample / specimen being tested.
Fusion	A process for bonding a polymer by heating and melting two polymer surfaces and pressing the surfaces together. This forms a common over-structure, created by co-crystallisation of the macromolecules beyond the weld interface.
Stress whitening	The colour change associated with cold drawing of a semi-crystalline polymer. It is thought to result from a combination of micro void and craze formation when the applied local stress exceeds the yield stress.
Fusion Interface	The pipe and fitting contact faces that are joined together in the heat fusion process.
Void	A hole or empty space that is formed within the fusion zone.
Lack of fusion	Absence of intermolecular diffusion, entanglement, and co-crystallisation at the fusion interface between two surfaces.
Micro ductility	Ductile plastic deformation across a fusion interface observed through low magnification (5 – 40x) light microscopy.

APPENDIX B

MICRO DUCTILITY

Assessment of micro ductility is made easier by being able to clearly identify brittle fracture both macroscopically and microscopically and is shown in the examples below.

Brittle fracture zones at the weld interface between the pipe and EF fitting will display little or no macroscopically visible plastic deformation, tearing or elongation. This is also the case in microscopic examination of a brittle fracture surface at the weld interface at low magnifications, for example Figures B.1 and B.2 at 6.4x and 16x magnification respectively.

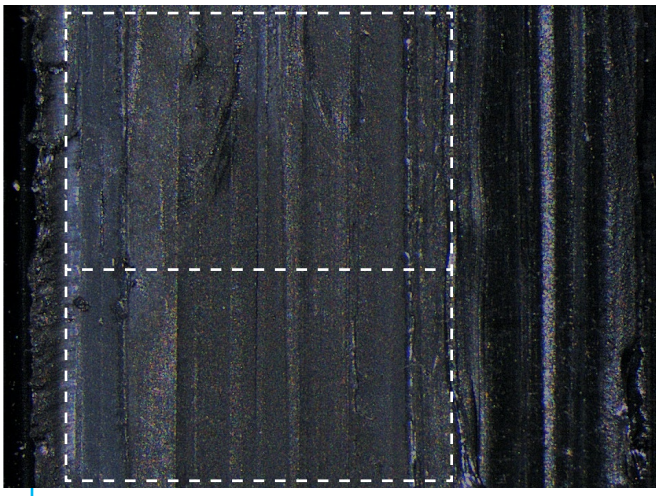

Figure B.1 – Brittle fracture zone on the EF fitting side of the weld at 6.4x magnification.

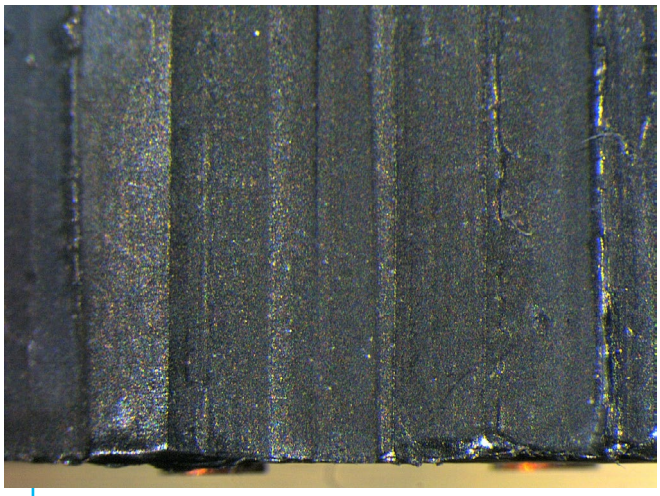

Figure B.2 — Brittle fracture zone on the EF fitting side of the weld at 16x magnification (bottom section of figure B.1).

Ductile fracture is characterized by material tearing and plastic deformation. Gross plastic deformation is easily detected by visual (macroscopic) examination. However, **micro ductility** may also be present and requires low (5-40x) magnification microscopic examination to confirm its presence. An example of micro ductility when viewed at 6.4x, 16x and 40x magnification through a stereo microscope is given in figures B.3, B.4 and B.5.

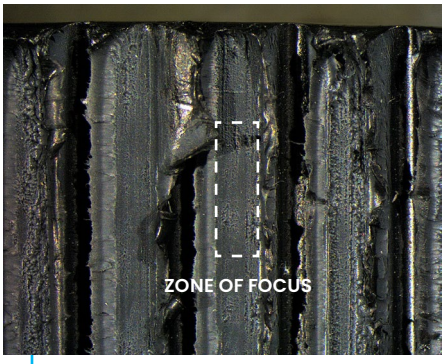

Figure B.3 — Micro ductility present in the fracture zone – viewed at 6.4x magnification. Note gross plastic deformation is present on each vertical side of the zone of focus.

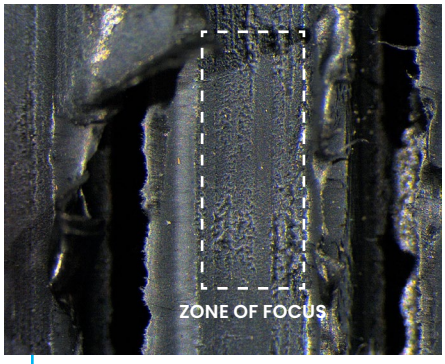

Figure B.4 — Micro ductility present in the fracture zone – viewed at 16x magnification.

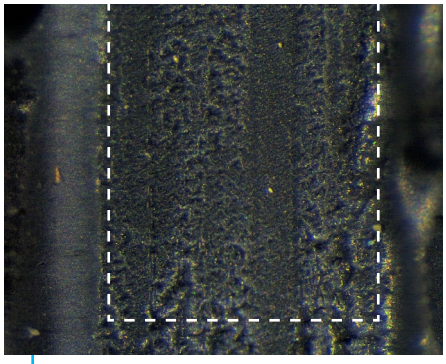

Figure B.5 — Micro ductility – viewed at 40x magnification.

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