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THE FATIGUE PERFORMANCE OF ELECTROFUSION TAPPING TEES SUBJECT TO CONTAMINATION

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Abstract

Electrofusion jointing is a common joint process used to weld polyethylene (PE) water pipe in the UK. For many years, the UK Water Industry has experienced a small number of premature failures of electrofusion fittings; this inevitably causes leakage. The common causes of critical failures have been highlighted and as a result of this, a testing programme was designed and implemented to assess the fatigue performance of electrofusion tapping tees if they were to be installed by 'bad practice'. A fine china talc was used to replicate contamination in the field. The results suggest that failures associated with fatigue are possible in a relatively short space of time on tapping tees when they are subject to contamination. The pressure ranges used in the fatigue regime aimed to replicate the potential magnitude of surge pressures that can be experienced in water distribution mains.

Keywords: *polyethylene pipe, electrofusion, fatigue, surge.*

1 Introduction

The use of plastic pipes within the UK Water Industry dates back to the 1950s. Initially polyvinyl chloride (PVC) was predominant, but this has gradually been superseded by polyethylene (PE) which has become a standard material for pressure pipe systems in the water industry. Current research shows that PE will exceed its expected design life of 50 years by another 50 years at operating temperatures of between 10 and 25 °C [1].

Buttfusion and electrofusion jointing are the common welding methods used to join PE pipes. Buttfusion involves the use of a hot-plate to melt the ends of the pipe; the heated pipes are then forced together to form the joint. Electrofusion jointing uses electricity to heat a filament wire that is manufactured into the carcass of the fitting; this melts the pipe and fitting locally and as they cool the bond is formed. Many PE joints (especially electrofusion joints) are potentially installed in difficult working environments; for example trenches that are open to the elements. In order to ensure joint integrity, best practice procedures must be followed.

In comparison with buttfusion welding whereby fully-automated machines can be used by preference, electrofusion welding is somewhat a more ‘manual’ jointing procedure. Here the operative needs to follow specific preparation procedures that are highlighted in Water Industry Specifications (WIS) and manufacturers’ guides to best practice. Special care needs to be taken to ensure that the fusion zone (jointing area) is dry and clean of any contaminants such as dirt, dust and water. Any contaminants present in the jointing interface could compromise the integrity of the asset. Research has shown that failures can occur in PE water distribution networks, specifically at the joint [2]. An independent study of the National Sewers and Water Mains Failure Database analysed data between 2005 - 2009 and concludes that there is a failure rate of 8 failures per 100 km per year [3]. At the time of this study, the database recorded a total length of 65,279 km of PE pipe in the UK. Contrarily, analysis of the same database [2] revealed PE to be the best performing material with regards to failure rates.

A surge can be defined as a sudden change in pressure [4]. The effects of surge on PE water distribution networks have been well researched and documented since the late 1990's [5]. Fatigue can be described as the repetition of such events that can cause a reduction in the long-term strength of material. Bowman [6] explains that pipe systems may be subject to two different types of 'fatigue': firstly, a diurnal fatigue by which the demand on the network causes fluctuations in pressure (≤4 bar), ranging between 3.7×10^4 cycles and 9.0×10^4 cycles in a 50 year design life; secondly, the operation of pumps and valves in the distribution network (>6 bar). It is important to note that during either event, the material will experience periods of constant pressure in addition to fluctuations.

With regards to fatigue performance of polymer materials, there is a wide range of information available on analysis techniques and methods [7]. Hydraulic (pressure) fatigue tests can be long in duration giving the possibility of long test times required for worthy data generation. However, it is arguable that pressure testing relates to the long term performance of the asset compared to typical mechanical destructive testing.

Electrofusion failures within the UK water industry has been well documented with the three main causes being: poor scraping, misalignment (including problems associated with ovality) and contamination [2, 8, 9, 10]. Note that these issues are all associated with on-site practice (workmanship). Although electrofusion failures are well researched, the problem is far more complicated than providing one simple solution.

Two of the three aforementioned workmanship issues can arguably be overcome by the implementation of training and tooling provided to the operative. However, contamination is an environmental issue that may be harder to overcome. Previous research has shown that applying a talc contaminant to the jointing interface prior to welding has a detrimental influence in joint performance [11]. It was on this basis that a short term test was developed to ensure that all electrofusion fittings in the UK carried a certain resistance to contamination [12]. One test that is incorporated into the WIS known as the ‘resistance to contamination: short term burst test’ [13, 14] for electrofusion joints encompassing both electrofusion coupler and saddle (tapping tee) fittings. Here, a talc contaminant is applied to the pipe prior to the assembly of the fitting. Particle size and distribution with regards to contamination is extremely important as some particulate contaminants have a greater influence on the fracture toughness of an electrofusion joint [15, 16]. Furthermore, the WIS test specifies fine china talc with a particle size of 0.63 µm – 6.3 µm.

Specimens prepared to the aforementioned test are attached to a hydraulic rig capable of increasing the internal pressure at a constant rate of 5 bar/min until failure. For electrofusion couplers, failure should not be below the nominal pressure (PN) rating of the pipe multiplied by 2.5 (PN x 2.5); for electrofusion saddle fittings a minimum pressure of 18 bar must be achieved. A successful joint would indicate that it has some resistance to contamination, however this does not mean that the joint will not fail in service if best practice principles are *not* followed on site. Furthermore, this short term test does not relate to the long term performance of the joint.

Therefore, an experiment was designed to observe the effects of fatigue-life of electrofusion tapping tees subject to a particulate contaminant; using the WIS short term burst test as the starting point of the experiment.

2 Experimental Procedure

The subjects of the experiment were PE pipe and fittings from the same UK manufacturer. Pipes were 110 mm diameter with Standard Dimension Ratio (SDR) 17 of grade PE100 with an average density of 950.1 kg/m^3. The tapping tees used were injection moulded PE100 grade fittings, although the same product was used consistently through the test programme, all tapping tees were purchased 'off-the-shelf'.

Electrofusion tapping tees are commonly used to connect the water distribution main to the end user (customer). There are many different designs of tapping tee but the principle of welding the fittings are relatively similar. A compressive force is applied between the fitting's fusion interface and the host pipe. This force is usually achieved by a top-loading G-clamp or an under-clamping strap and should also ensure that the fitting does not move during the welding process.

The test specimens were prepared in accordance to the WIS short term burst test [13]. The specification recommends that the contaminant is uniformly applied to the pipe using a device designed to a recommended specification. In this experiment the contaminant was evenly and conservatively brushed onto the pipe using a 25 mm wide soft bristle paint brush. This method is acceptable for assemblies which fuse with limited pad area [7]. To add an element of quality control, all specimens were created by the same operative.

With regards to the application of hydraulic pressure, the inlet was attached to the stem of tapping tee as opposed to the service outlet end recommended by the WIS. This was to mitigate the purchase/design of a mechanical end cap. Furthermore, a 25 mm diameter electrofusion end cap was welded to the service pipe outlet leaving less than one diameter of 25 mm (PE80) pipe exposed.

Sections of the 110 mm diameter pipe were cut perpendicularly to approximately 320 mm in length allowing approximately one diameter of pipe either side of the fitting. The pipe product used had a protective skin surrounding the host pipe; this was removed to expose the pipe's core. With 'skinned' products, no extra preparation is required (i.e. pipe scraping) once the skin is removed. All specimens were welded at an ambient temperature 21 (±1.5) °C – once welded the specimens were left for a minimum of 24 hours prior to testing. The testing media used was tap water; left uncovered for a minimum of 12 hours to aid the removal of air. The specimens were filled with water prior to assembling to the fatigue test machine to avoid air unnecessarily entering the system.

An experimental hydraulic piston was designed and built to be retrofitted to an existing servo-hydraulic fatigue testing machine. The rig was designed to house two tests: (i) the WIS short term burst test and (ii) a dynamic load (fatigue) test. A calibrated pressure transducer was used as the primary feedback in the closed-loop control system. It is important to note that a servo-hydraulic control unit is traditionally used to control the main actuator (load cell/position control), however, for the purpose of this testing programme both software and hardware alterations of the control unit needed to take place in order for the pressure transducer to govern the test. Furthermore, the load cell was not made redundant but simply switched to be the secondary feedback loop; the pressure transducer being the primary. Figure 2.1 illustrates a schematic of how the experimental rig and the tapping tees were assembled for the tests.

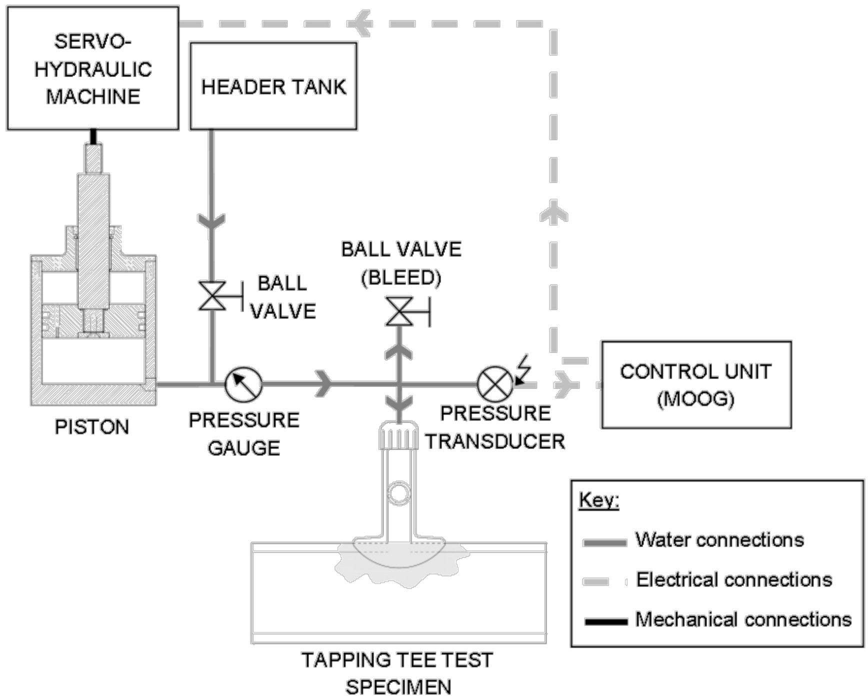


Figure 2.1 - Schematic showing all components

(i) <u>Short term burst test</u>

The aim of this test was to establish an average failure pressure for electrofusion tapping tees welded to the specification of the 'talc test'; this was deemed the maximum pressure of the jointing system $(P_{MAT,MAX})$. Once established, this value was used as a benchmark for the dynamic loading long term test. It is important to note that the ramp rate for both the short term burst test and the dynamic load test were to be the same, as the aim of the dynamic test was to establish a link between pressure range variation with respect to fatigue life of electrofusion tapping tees. The WIS [13] recommends a ramp rate of 5 bar/min but this was deemed too slow for reasonable test durations in the fatigue tests. Therefore, the ramp rate was increased from 5 bar/min to 25 bar/min. The short term burst test was carried out four times per ramp rate. The results from this are shown in Table 2.1. The results show that there were little difference in the average and median failure pressures of approximately 25 bar $(= P_{MAT,MAX})$. In addition to these tests, several identically made specimens were tested at a third party test house comparing results with those observed with the experimental rig to benchmark the apparatus.

Test No.	Failure pressure (bar) at 5 bar/min ramp rate	Failure pressure (bar) at 25 bar/min ramp rate	Third party testing at 5 bar/min (bar)
1	24.6	22.3	21.1
2	25.8	26.5	23.4
3	25.7	25.4	-
4	23.2	23.6	-
Average failure pressure	24.8	24.5	22 .3
Median failure pressure	25.2	24.5	

Table 2.1 - Failure pressures at different ramp rates

(ii) <u>Dynamic load (fatigue) test</u>

A trapezoidal loading pattern was followed for the basis of the fatigue test and the results plotted as pressure vs. number cycles to failure as per Joseph et al. [17]. The mean pressure was fixed for all loading patterns and the pressure ranged varied. The ramping rate (pressure increase/decrease) was fixed at 25 bar/min therefore frequency varied for each loading pattern. The short term burst test highlighted $P_{MAT,MAX}$ of the contaminated tapping tees and the pressure range of the trapezoidal loading patterns followed percentage decrements from 90% - 40% of $P_{MAT,MAX}$, i.e. for; $n \in \{90, 80, \dots 40\}$:

$$P_{RANGE} = n\% \times P_{MAT,MAX} \tag{1}$$

The mean pressure was fixed at 12.5 bar; calculated as half of the average failure pressure from the short term burst test:

$$P_{MEAN} = {}^{1}/_{2} \times P_{MAT,MAX} \tag{2}$$

The resting period at the top and bottom of each cycle was fixed at two-thirds of the ramp time from the mean pressure to the amplitude, thus:

$$t_{REST} = {}^{2}/_{3} \times t_{RAMP,AMP} \quad (3)$$

The loading patterns for the fatigue test are shown in Figure 2.2.

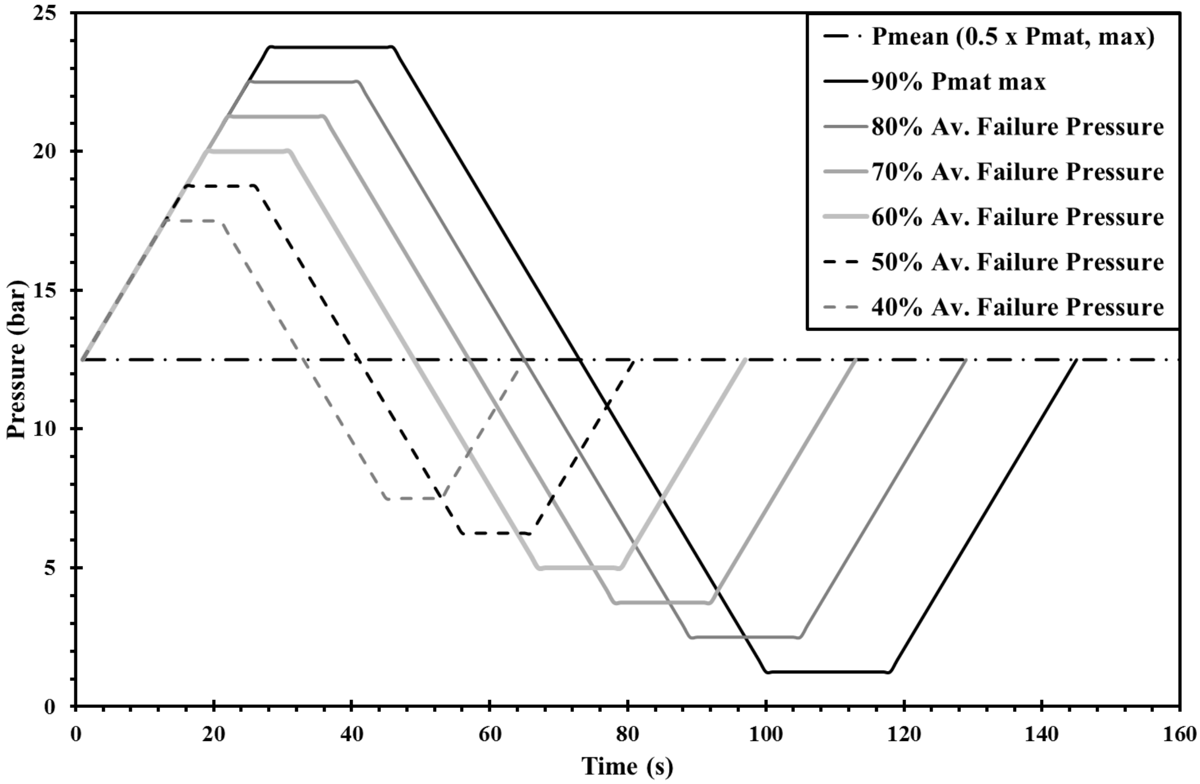


Figure 2.2 - Trapezoidal loading patterns for dynamic (fatigue) test showing 1 cycle

$$\left(where;\ P_{MAT,MAX} = 25\ bar, P_{MEAN} = 12.5\ bar, P_{RANGE} = n\% \times P_{MAT,MAX}\right)$$

$$(For;\ n \in \{90, 80, \ldots 40\})$$

In addition to the tests on the contaminated tapping tees, two specimens were made to best practice principles, i.e. with no contamination. These were tested at the highest pressure range 90% of $P_{MAT,MAX}$ in order to provide a direct comparison between contaminated and best-practice joints.

3 Results

Figure 3.1 shows the results for the fatigue test in a form similar to a stress-life (S-N) curve. Due to the complex geometry of the tapping tee the 'stress' was not calculated as there will inevitably be differential stress concentrations as the geometry changes throughout the fitting. Therefore, the results are expressed as pressure range vs. number of cycles to failure.

For this testing regime, a failure can be described as the joint not being able to maintain pressure. This was usually when the delamination of the bonding surface was such to create a clear leak path.

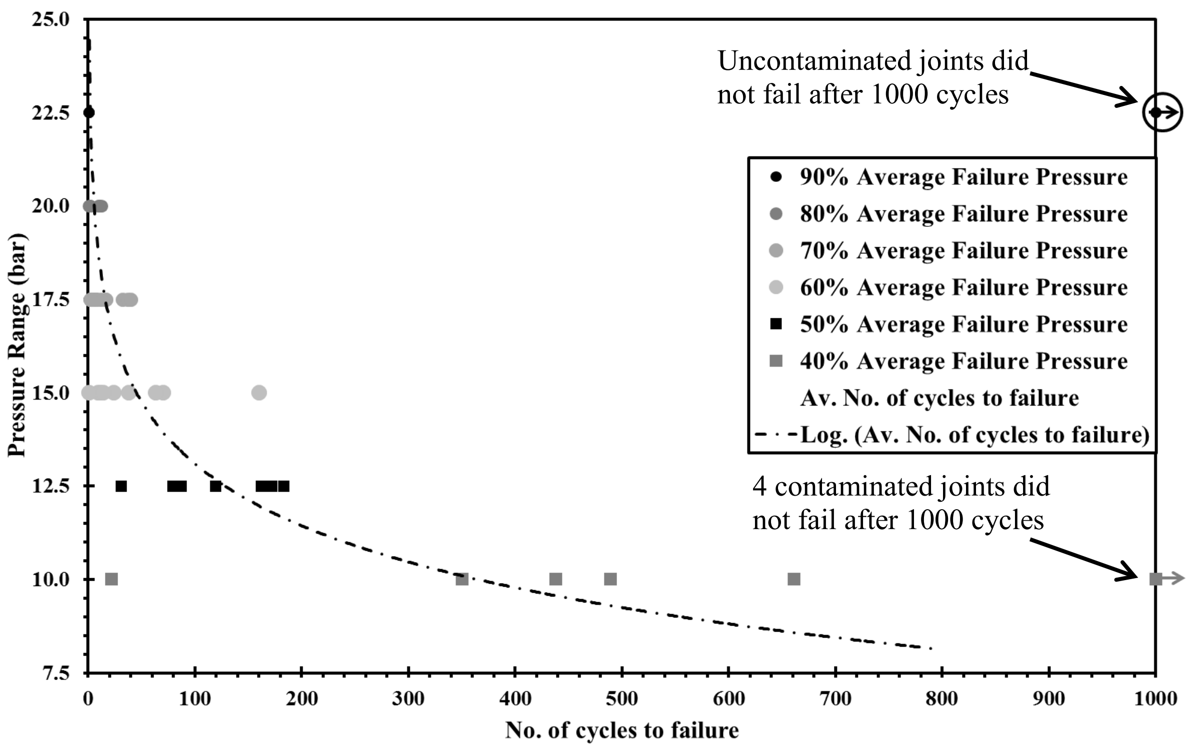


Figure 3.1 - Pressure Range vs. Number of cycles to failure for the dynamic (fatigue) loading test $(where;\ P_{MEAN} = 12.5\ bar)$

It is important to note that the fatigue test was stopped if a specimen did not fail after 1000 cycles as this testing programme is classed as low cycle fatigue. A minimum of eight tests were conducted for each pressure range with the exception of the 90% $P_{MAT,MAX}$ pressure range where three specimens failed to reach one cycle. In contrast, the two tests on "perfect" , uncontaminated joints which were conducted at this highest pressure range (circled in Figure 3.1), did not fail after being subject to 1000 cycles. In the 40% $P_{MAT,MAX}$ pressure range, five tests were successful, in that they failed within 1000 cycles, however, four tests did not fail (i.e. exceeded 1000 cycles). These are highlighted in Figure 3.1

It can be observed that as the pressure range decreases, the distribution of failure increases. This is becomes evident in the 10 bar range whereby one specimen failed below 50 cycles and some did not fail after 1000 cycles. It can be argued that this low pressure range pushes the boundary of the short term fatigue life of the product. Based on the indicative logarithmic line plotted against the mean number of cycles to failure (Figure 3.1), it can be said that if the pressure range were to be dropped further, there is a likelihood that most specimens would successfully reach 1000 cycles without failure. Hence there is an argument that for low pressure ranges (<10 bar) there may be a fatigue limit in this testing regime.

Using the experimental data in Figure 3.1, a regression analysis was performed and the 95% confidence limits obtained. Figure 3.2 indicates the average number of cycles to failure with the 95% confidence limits on pressure range Vs. Log number of cycles to failure. The limits clearly show two results that lie well below the lower boundary at 15 and 10 bar pressure range as highlighted in Figure 3.2.

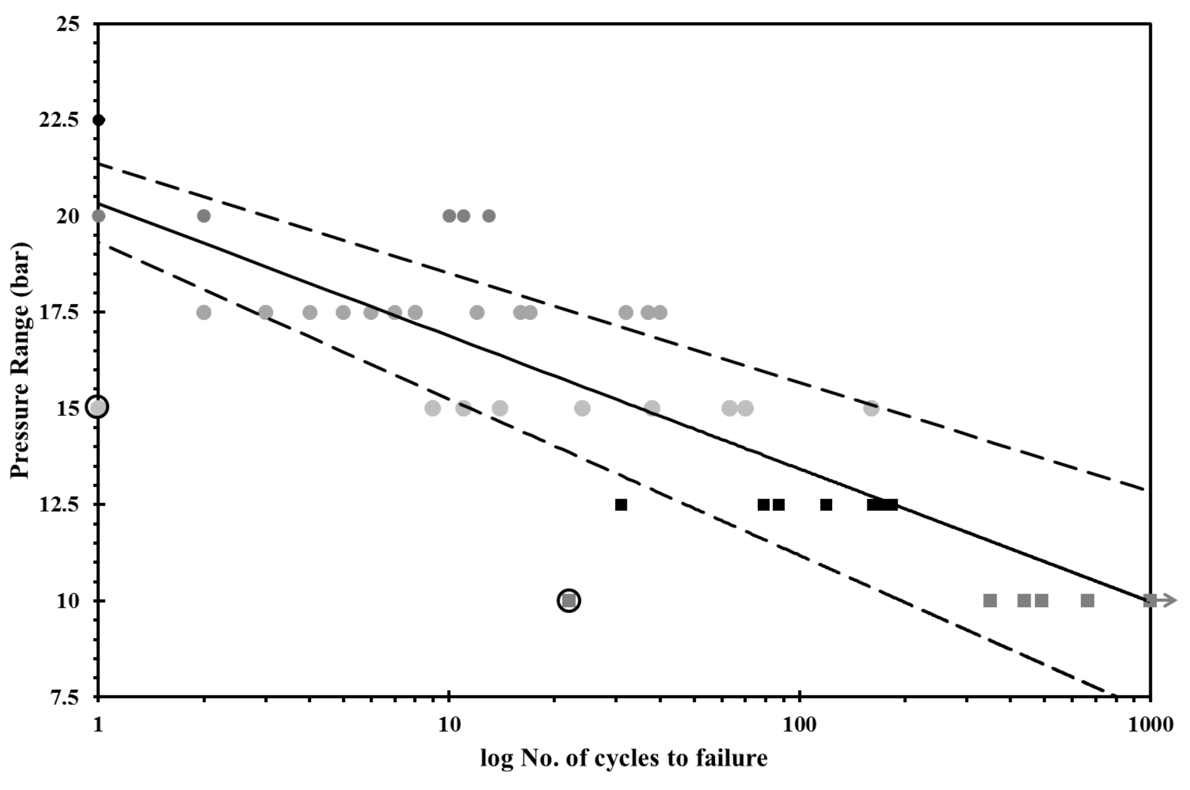


Figure 3.2 Pressure Range vs. Log Number of cycles to failure

4 Leak Path Analysis and Crushing Decohesion Test

Following the fatigue testing, the leak paths of each joint were observed by using a basic hand pump to produce a flow of water through the fittings. Each joint was then subject to a crush decohesion test (ISO 13955 [18] so that the bonded surface could be observed in order to explore the nature of the failure.

The crush decohesion test (ISO 13955 [18] instructs that pipes are inserted into a device that is able to crush the specimen at a rate of 100 mm/min (1.67 mm/s) until double the wall thickness of the pipe is achieved. In our case a table vice was used and Figure 4.1 illustrates the testing apparatus for electrofusion tapping tees; where d_p is the distance between the jaws of the crushing device. If the fitting (the tapping tee) does not yield away from the host pipe after the crushing exercise, a lever may be used to prise the fitting away from the pipe - no impact forces are allowed.

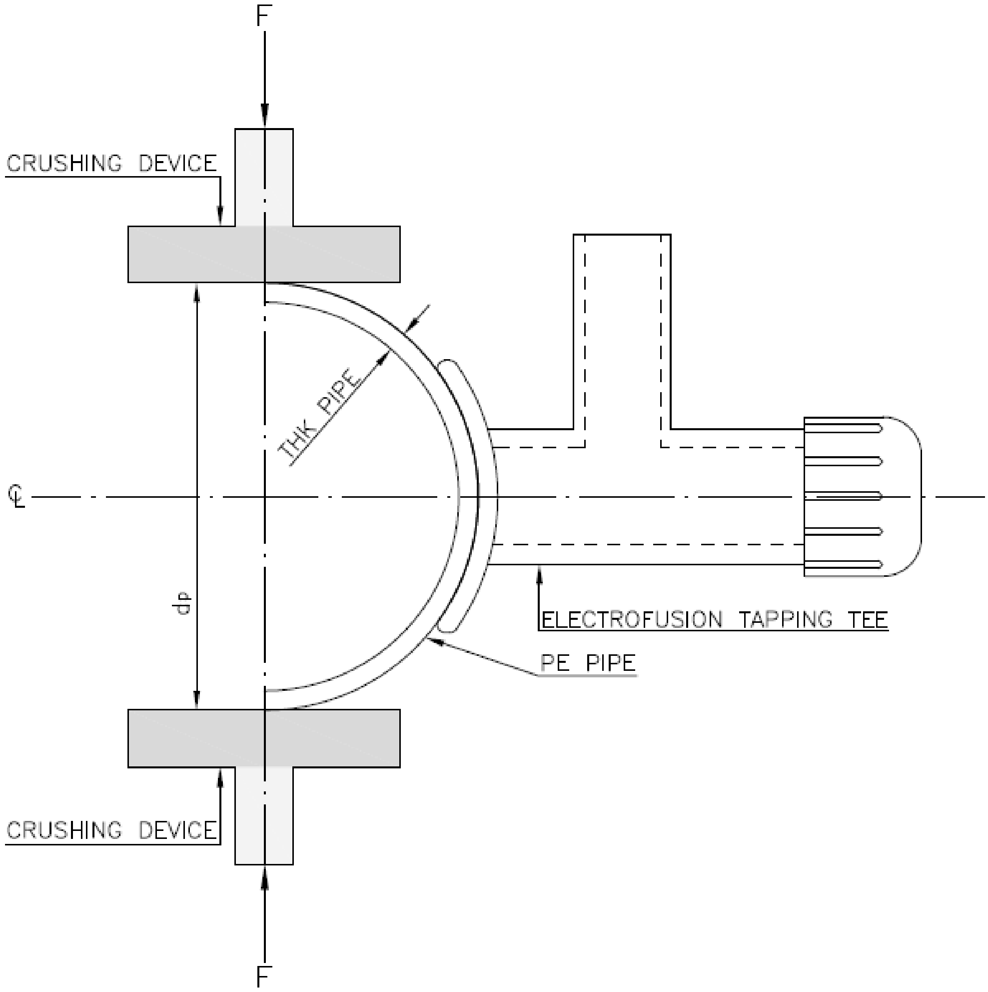


Figure 4.1 Indicative sketch of crushing decohesion test (tapping tees)

With reference to Figure 4.1, as d_p decreases during the crush test, the forces present should induce failure about the jointing interface by producing a crack that propagates as the crush test is performed.

Figures 4.2 and 4.3 compare the bonded surfaces of a joint that had been subject to the talc contaminant and a joint that had been made to best practice principles. Figure 4.4 shows examples of specimens that failed under the fatigue testing regime.

Figure 4.2 shows an aerial view of the pipe and fitting when the crushing device reached its maximum distance. Once the maximum displacement was reached in the crushing test, the fitting was further removed from the host pipe by using a relatively small amount of force which was applied by hand, just using the stem of the tapping tee as a lever. As can be seen in Figure 4.2, there were small black marks on the pipe where it appears a small amount of bonding had taken place between pipe and fitting. However, indentations on the surface of the pipe from where the filament wires were embedded into the pipe show that they may have been offering some structural support to the assembly.

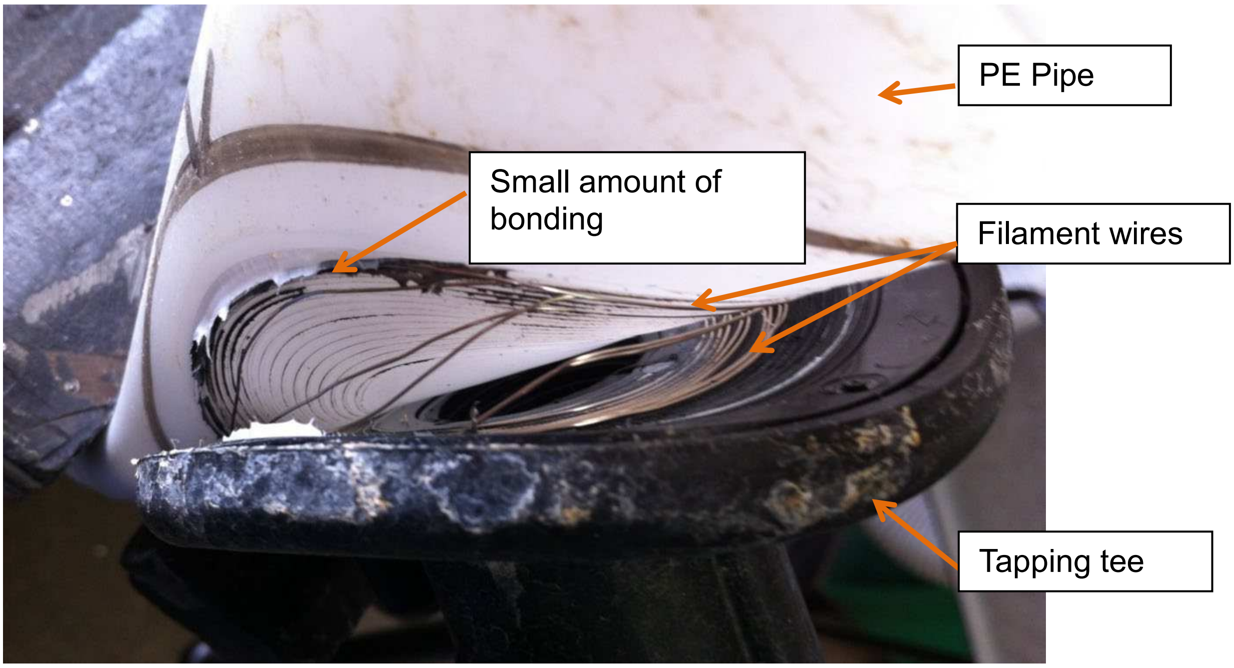


Figure 4.2 Aerial view of contaminated specimen following the crushing decohesion test

Small amounts of ductility are visible about the outer circumference of the fusion zone. Note that this area was where the filament wires were mostly embedded into the parent pipe. It is important to note that the failure of the joint when subject to this test should be classed as a brittle failure. However, the ductility observed is very small and localised about the outer circumference of the fusion interface; more specifically, either side of the indentations on the parent pipe created by the filament wires during the welding process.

As a comparison, the crushing decohension test was conducted on a specimen that was welded to best practice. Figure 4.3 shows the specimen after it has been subject to the full extent of the crushing device. As can be seen, the specimen was just beginning to fail on the outer part of the fusion zone but still remains fully adhered to the PE pipe when the maximum crushing distance is reached; suggesting that a ductile failure would occur.

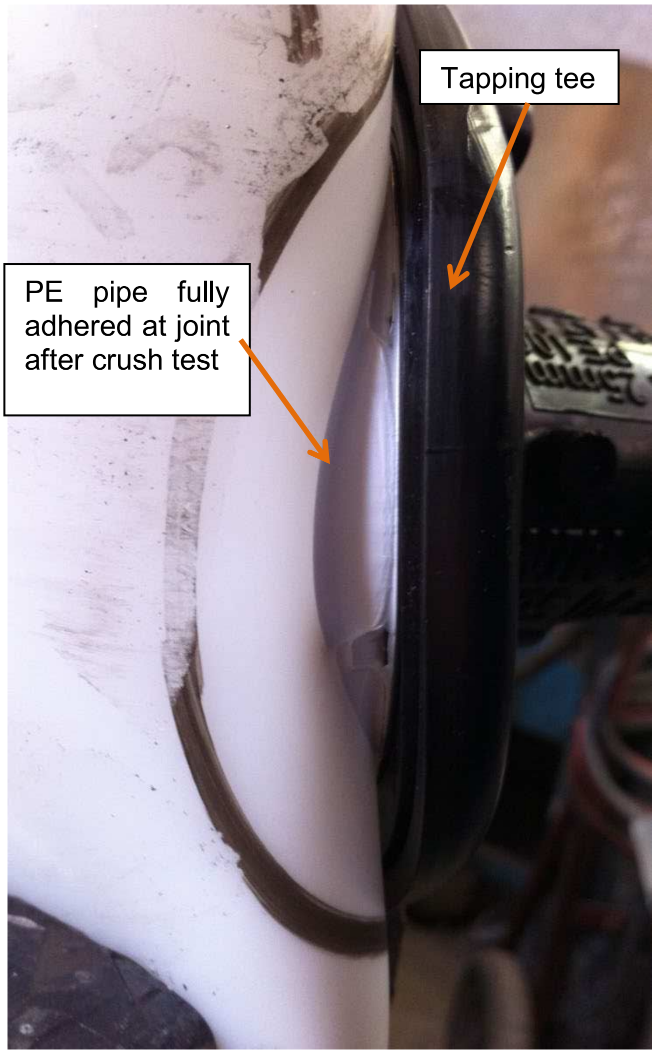
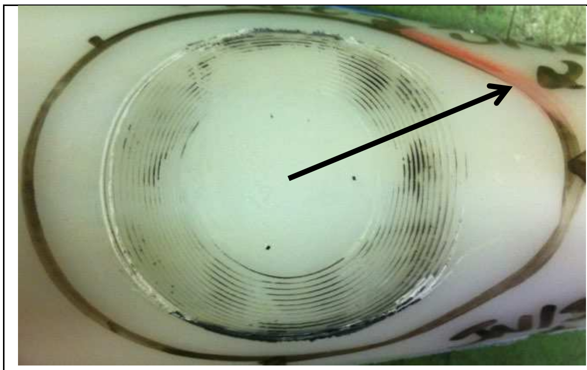


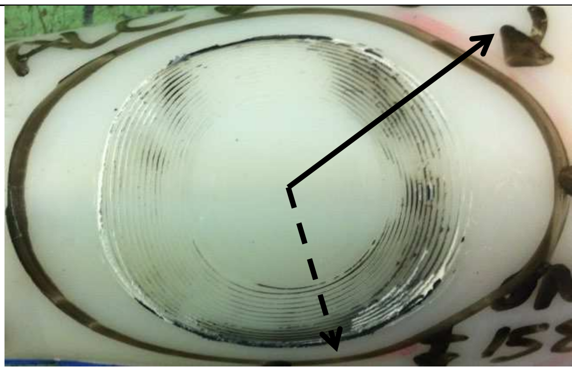
Figure 4.3 'Perfect', uncontaminated specimen following the crushing decohesion test

The assembly was further crushed on the opposing side of the fitting assembly in an attempt to yield the specimen but with no success. It can also be seen (in Figure 4.3) that there is very little opportunity to insert a lever to persuade the specimen away from the pipe. ISO 13955 [18] states that no impact forces shall be used to yield the fitting from the pipe, therefore using only a lever to remove the fitting from the pipe was a next to impossible task. It was therefore concluded that the specimen would fail in a fully ductile manner. This comparison further enforces the detrimental nature that contamination has on joint integrity.

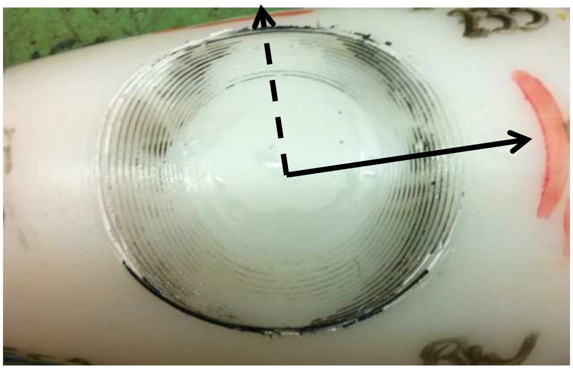
For illustration purposes, for each pressure range tested, a contaminated specimen was selected whose number of cycles to failure was the closest to the average number of cycles to failure. Figure 4.4 figure shows pipe surfaces following the crush decohesion test and also indicates the approximate leak paths. The leaks were classed as major and minor leaks, where a major leak can be described as the primary flow of water; whereas a minor leak would be almost a trickle of water that is subsidiary to the major leak.



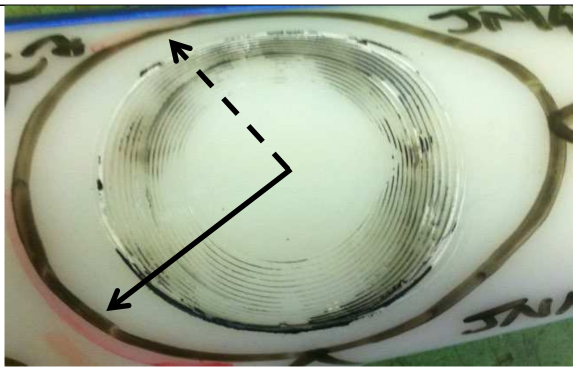
(a) 90% $P_{MAT,\ MAX}$ Pressure range



(b) 80% $P_{MAT,\ MAX}$ Pressure range



(c) 70% $P_{MAT,\ MAX}$ Pressure range



(d) 60% $P_{MAT,\ MAX}$ Pressure range

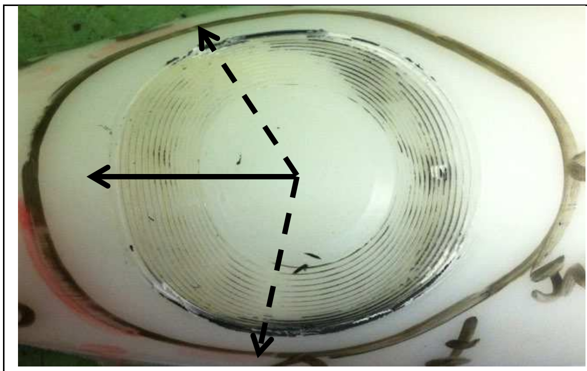
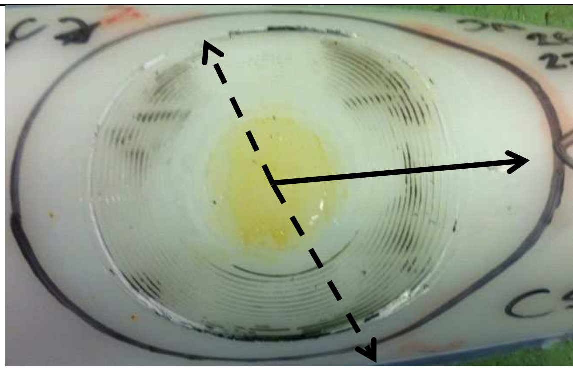
	
(e) 50% $P_{MAT, MAX}$ Pressure range	(f) 40% $P_{MAT, MAX}$ Pressure range

Figure 4.4 Pipe joint surfaces following fatigue test to failure, leak path test and crush decohesion test. The solid lines indicate major leak paths and dashed lines indicate minor leak paths

5 Discussion and Conclusions

Post-failure analysis of the contaminated joints revealed very little bonding between the electrofusion tapping tee and the host pipe, therefore it can be assumed that all specimens failed in a brittle manner. In all of the samples tested, the effects that contamination has on the adhesion of the fitting to the parent pipe are clear, in that, when compared to the "perfect joint" (Figure 4.3), the fittings were easily fully removed from the pipes using the crush decohesion test (Figure 4.4). The most logical failure mechanism for brittle failures would be crack propagation [19] of the jointing surface. However this was proved not to be the case. As can be seen in Figure 4.2, sections of the electrofusion filament wire were embedded into the host pipes. This suggests that wire itself may have been offering some degree of structural integrity if little or no polymer bonding were present. Bonding appears to be the best at the outer circumference of the fusion zone (See Figures 4.2 and 4.4). Here, only a very small amount of ductility can be seen and it is believed that this bonding is located either side of the indentations caused by the filament wires during the welding process. Furthermore, failure (leak) paths appeared to be random which suggests that the product itself has no obvious weak points. Minor leak paths seem to become more predominant as the pressure range is decreased in the fatigue testing regime. For example, the specimen in Figure 4.4(a) (90%

$P_{MAT,\ MAX}$) has one clear major leak path, whereas in Figure 4.4(f) (40% $P_{MAT,\ MAX}$) the specimen has one major leak path and two minor leak paths. This may suggest that the lower pressure ranges promote crack growth under dynamic loading; potentially in a circular manner.

With regards to the two anomaly results that sit well below the 95% confidence limits (circled in Figure 3.2), there were no obvious reason why these failed prematurely. It can therefore be assumed that there may have been a variation in the specimen preparation procedure.

For typical PE pipe products, prior to assembly of an electrofusion fitting, the oxidised layer on the outside of the PE pipe needs to be removed. This is usually achieved by the use of a mechanical or hand scraper. Mechanical scrapers are generally preferred where possible as they leave a more uniform surface for jointing and scraping tends to be more consistent from operator to operator. As mentioned above, the PE pipe product used for this experiment had a protective polypropylene skin that needed to be removed prior to assembly of the fitting and welding. Once removed it revealed the PE pipe with a smooth extruded external surface of which no additional scraping preparation was required. Therefore, brushing the talc contamination on the pipe surface is arguably more uniform than if it were to be brushed on the scraped surface.

For the fatigue testing programme, a fixed mean pressure of 12.5 bar was used. This value can be compared to the service pressure of a distribution main and thereby the cycles relate to the increase/decrease in pressure that may be expected in a water distribution network. The mean pressure (12.5 bar) would arguably be too ‘high’ for distribution mains of 110 mm diameter; also, the pipe used was rated with a minimum required strength (MRS) of 10 bar (SDR 17). It was in the remit of the fatigue experiment to accelerate the time to failure. It is not uncommon in fatigue tests to use an 80°C bath to house specimens to decrease the time to failure [6]. However, in this experiment it was decided to test at ambient temperature and use an increased pressure as the failure accelerant. Furthermore, this testing programme has shown that fatigue failures can occur on contaminated electrofusion joints in relatively short spaces of time but at higher than expected 'operating pressures'. From the outcomes of this experiment, a secondary testing programme has been developed to relate the findings from this experiment to typical pressures in distribution mains with the aim of predicting the asset life of a contaminated joint. This will be accomplished by using a fixed pressure range, varying the mean pressure.

As previously mentioned, there was the possibility of a fatigue limit in the current testing programme as some specimens did not fail after 1000 cycles. Typical fatigue tests on PE pipe usually indicate a high number of cycles until failure ($>10^5$ cycles); this testing programme has illustrated low cycle fatigue failures at raised pressures using a talc contaminant to replicate poor workmanship that may be experienced in the field. However, for lower pressure ranges, it would appear that the prediction of failure becomes more difficult. When fatigue testing, there will always be an element of scatter in testing results. Bowman [20] explains with regards to fatigue testing of electrofusion fittings, the fatigue life can vary by a factor of ten. Furthermore, different grades and batches of PE can give different fatigue strengths. This may explain the large amount of scatter in the results from this experiment as the tapping tee fittings, although a single product were tested , were purchased off-the-shelf; may have come from difference batches in manufacture.

Previous research [11] has shown that the talc contaminant is a 'worst case scenario' and therefore the short term burst test depicted in the WIS is arguably a subjective test in relating poor workmanship to the long term performance of an electrofusion joint. However, the test can quickly assess the performance of different electrofusion products compared to long term hydrostatic tests that can prove to be costly. This dynamic loading test programme aimed to make the short term burst test more realistic and to give an indication of how electrofusion tapping tees would perform at various pressure ranges under cyclic load. As water distribution systems do not operate at a constant pressure and fluctuate due to various reasons such as the start/stop of pumping stations [21]; it can be argued from the testing programme undertaken that fatigue failures could happen if the asset is installed incorrectly.

To conclude, the experimental data shows that joint failures associated with fatigue are possible on talc contaminated joints under the proposed testing parameters. Although PE pipe has good short term resistance to increases in pressure (i.e. surge) in a nominal working scenario, this research suggests that if a product were to be instsalled incorrectly, the asset may fail to reach its expected 50 year design life.

Acknowledgments

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Nomenclature

MRS	Minimum Required Strength
PE	Polyethylene
$P_{MAT, MAX}$	Maximum pressure of the joint
P_{MEAN}	Mean Pressure
PN	Nominal Pressure
P_{RANGE}	Pressure Range
PVC	Polyvinyl Chloride
SDR	Standard Dimension Ratio
$t_{RAMP, AMP}$	Time taken to reach amplitude pressure
t_{REST}	Rest time
WIS	Water Industry Specification

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