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Fatigue Failure of Polyethylene Electrofusion Joints Subject to Contamination

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ABSTRACT

In the UK, water companies renew their aging water network using novel techniques and robust materials. The most common type of material used for network rehabilitation is Polyethylene (PE) pipe. A common method of jointing PE pipe is electrofusion welding. Here, electricity is used to heat a coil that melts the fitting and the host pipe of the same material. When the joint cools it forms a bond. However, premature failure of these can occur if best practice installation principles are not followed on site.

A novel experimental rig, designed to be retrofitted to an existing servo-hydraulic fatigue testing machine, has been used to cyclically pressurise PE fittings that have been created with a controlled element of 'poor workmanship'. Extensive fatigue tests have shown the relationship between joint failure and the dynamic pressures experienced in water distribution systems. Furthermore, the effects of poor workmanship have shown to have a detrimental effect on asset integrity.

A post-failure analysis of the fittings using non-destructive ultra-sonic methods has shown the failure paths of the fittings. Additionally, a bespoke ultra-sonic rig was designed and built to monitor the crack propagation of the fittings during live dynamic tests to confirm the mode of failure.

KEYWORDS: Polyethylene pipe, electrofusion, fatigue, ultrasonic analysis.

INTRODUCTION

Polyethylene (PE) has been used in the water industry since the early 1950's [1]. With the improvement of industry standards, the products developed from low density PE (LDPE) to today's high density PE (HDPE). This meant a more reliable and robust material was used in the industry which had a better resistance to crack growth than its predecessor, PVCu [2]. Today, the preferred material of choice for rehabilitating aging pipework is polyethylene (PE) pipe [3].

Two ways in which PE pipes are joined together are known as buttfusion and electrofusion (EF) welding. Buttfusion welding usually takes place above ground as the equipment used to join the pipes is quite large; whereas EF welding can be performed in smaller spaces such as trenches. Regardless of the welding method, in the UK a particular procedure highlighted in Water Industry Standard (WIS) 4-32-08 [4] should be followed to reduce the risks of premature failure due to poor installation. With regards to PE failures within the water industry, Trew & Mills [5] found a UK national failure rate of 8 failures per 100 km per year between 2005 - 2009.

A coupler can be used to EF weld two pipes together. However, to connect the host main to the end user, a service connection is usually used: these are known as tapping tees (See **Fig. 1**). To create an EF weld, the pipe surface needs to be scraped to remove the oxidised layer as well as being free from contaminants. Electricity can then be passed through the filament wire to heat the polymer of the host pipe and the fitting. Once a target heating time is reached, the fitting is required to cool and here the bond is formed. Pipes are typically pressure tested post-installation using water to check for leakage.

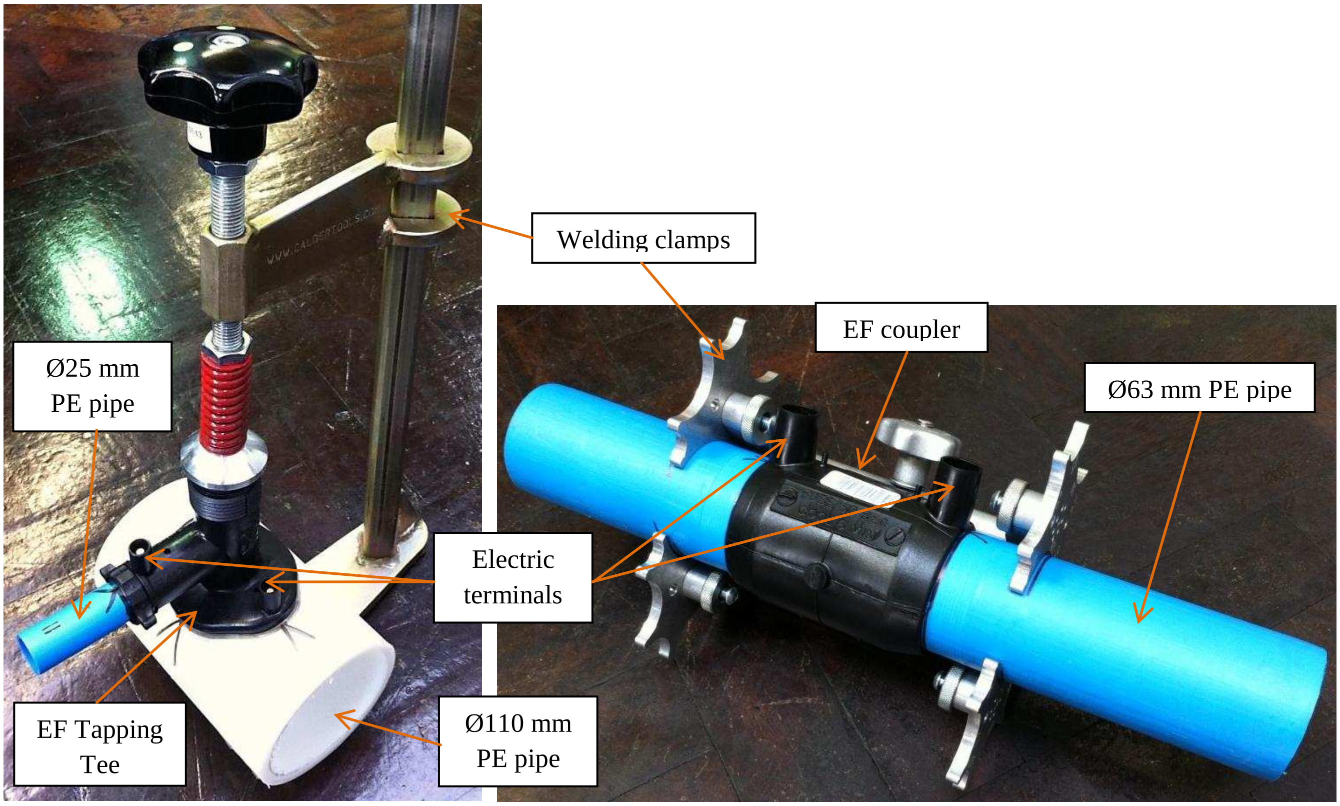

Fig. 1 Typical EF tapping tee (left) and coupler (right)

Research has shown that premature failures of EF joints in service can occur if the correct procedures are not followed, with the main causes of failure being poor scraping, misalignments and contamination [3, 6, 7]. Scraping of the pipe and correctly aligning the joint assembly can arguably be overcome by the implementation of appropriate tooling and training. However, contamination is an environmental issue that may be harder to overcome.

A surge can be defined as the fluctuation in pressure that occurs in a relatively short space of time [8]. With regards to water distribution networks, surges can occur with the opening and closing of valves as well as the starting and stopping of pumping stations [9]. Fatigue can be described as the loss of strength as a result of repeated loading over a period of time [10]. Bowman [11] explains that pipe systems may be subject to two types of 'fatigue': firstly, a diurnal fatigue by which the demand on the network causes fluctuations in pressure; secondly, the operation of pumps and valves changing pressures.

An experiment was designed to observe the fatigue performance of incorrectly installed EF joints. More specifically, EF tapping tees were subject to a talc particulate contaminant and tested under dynamic load.

FATIGUE EXPERIMENT

An experimental hydraulic rig was designed and built at the University of Sheffield to be retrofitted onto an existing servo-hydraulic machine. The rig was designed to house two tests; (i) a short term burst test specified in WIS 4-32-08 [4] and (ii) a dynamic (fatigue) test. The aim of the latter experiment was to observe the fatigue-life performance of EF tapping tees that have been subject to a talc contamination prior to welding. Talc is used as it replicates 'dirt' which could contaminate the weld. The fittings were identical products purchased off-the-shelf and the pipe was provided by a single manufacturer.

The fatigue test followed a trapezoidal loading pattern with a fixed mean pressure. The mean was calculated as half of the average failure pressure of five specimens tested to the aforementioned short term burst test. The pressure ranges for the trapezoidal loading regime was deduced as a percentage factor of the average failure pressure from the short term burst test. For details refer to [12].

The results from the experiment are shown in **Fig. 2**:

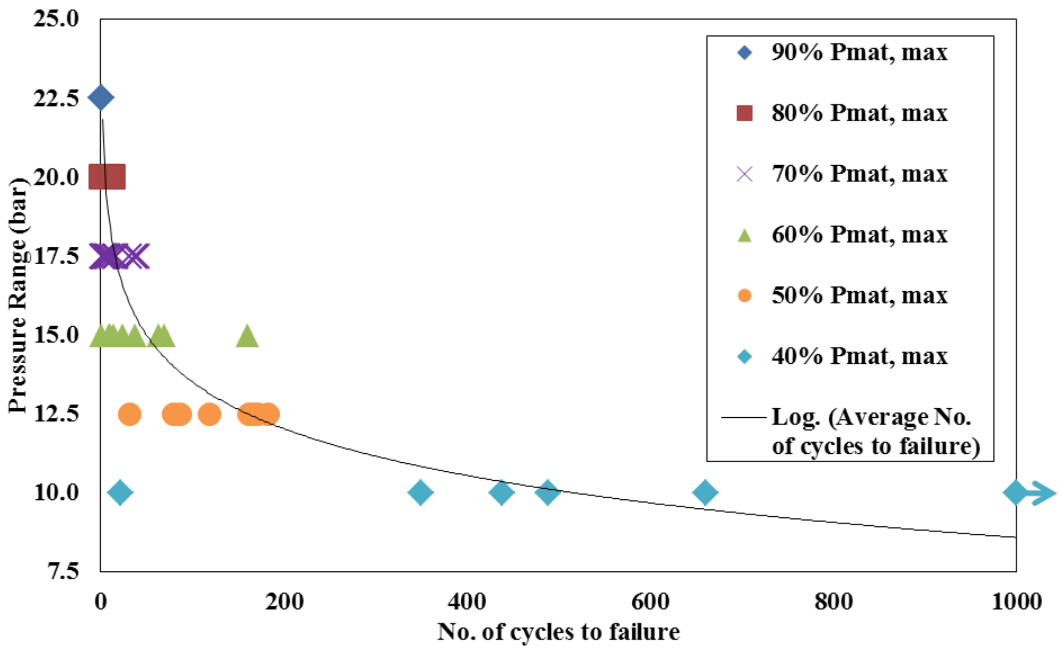

Fig. 2 Pressure range vs. number of cycles to failure for the fatigue test [12]

Fig. 2 suggests that as the pressure range is decreased, the spread of results becomes greater. Therefore the predictability of the number of cycles to failure becomes more difficult. Furthermore, at the lowest testing pressure range, 40% $P_{mat,\ max}$, shows results that exceed 1000 cycles which may suggest that there is a fatigue limit to this testing programme.

A secondary set of experiments are currently being conducted to observe the fatigue-life under a fixed range but variable mean; following the same trapezoidal loading pattern as mentioned previously.

With regards to **Fig. 2**, the most logical failure mechanism would be crack propagation [10] of the jointing surface. This hypothesis was explored further through the use of destructive and non-destructive methods of analysis.

DESTRUCTIVE TESTS

Destructive tests were performed to observe the failure modes by comparing contaminated joints visually to those that had been manufactured to best practice principles. A crushing decohesion test was performed in accordance with ISO 13955 [13] on EF tapping tees. The results showed the failure mode was brittle about the joint when the welding interface was subject to contamination prior to welding (**Fig. 3**). Notice that there are remnants of black polymer on the surface of the pipe and white polymer on the tapping tee where it appears a bond was beginning to form. Filament wires also appear to be still embedded into the host pipe.

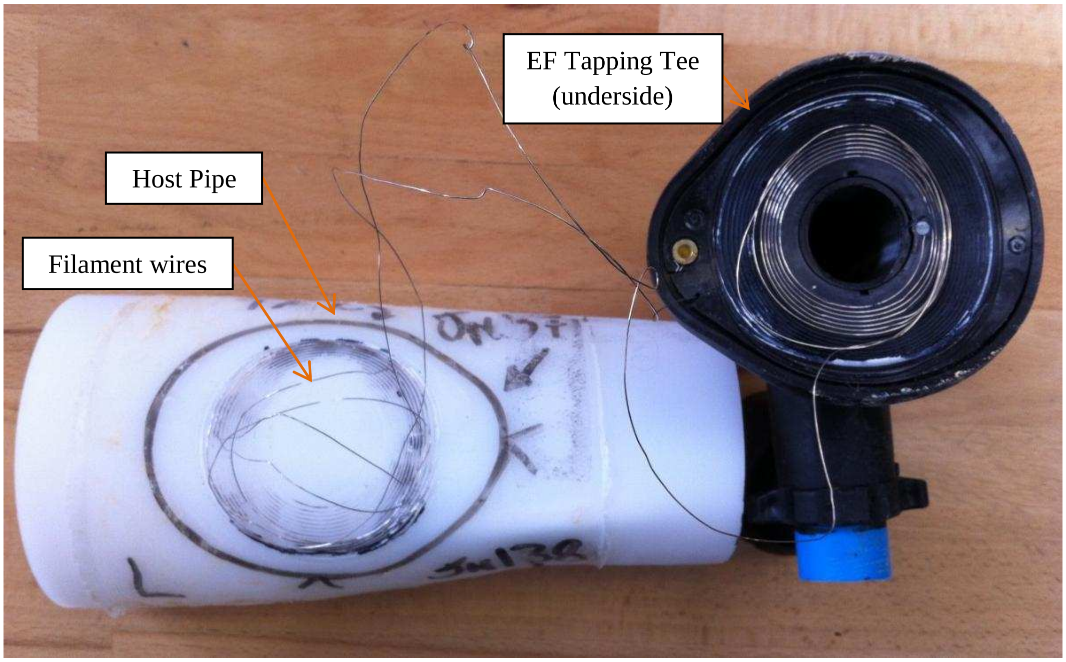

Fig. 3 Talc contaminated specimen subject to crush test

Contrarily, joints welded to best practice principles showed fully ductile behaviour about the jointing interface. **Fig. 4** shows the tapping tee after it was subject to the maximum crushing distance. There appears to be preliminary signs of crazing about the jointing interface after the pipe had been crushed. It is interesting to note that removing the tapping tee from the host pipe proved extremely difficult. This was mainly because there was minimal room to operate a lever to prise the fitting away from the pipe. Secondly, the joint had a distinct difference in mechanical strength compared to the brittle failure of the contaminated joint; which fell apart during the crush test.

The decohesion test proved useful in showing the comparable difference in strength and failure mode between joints that are subject to contamination and joints done to best practice principles.

As **Fig. 3** shows evidence of bonding beginning to take place it was assumed that the crack growth would be visible if non-destructive methods of analysis were used to observe the crack growth (i.e. leak paths) of joints failed to the fatigue testing regime highlighted in **Fig. 2**.

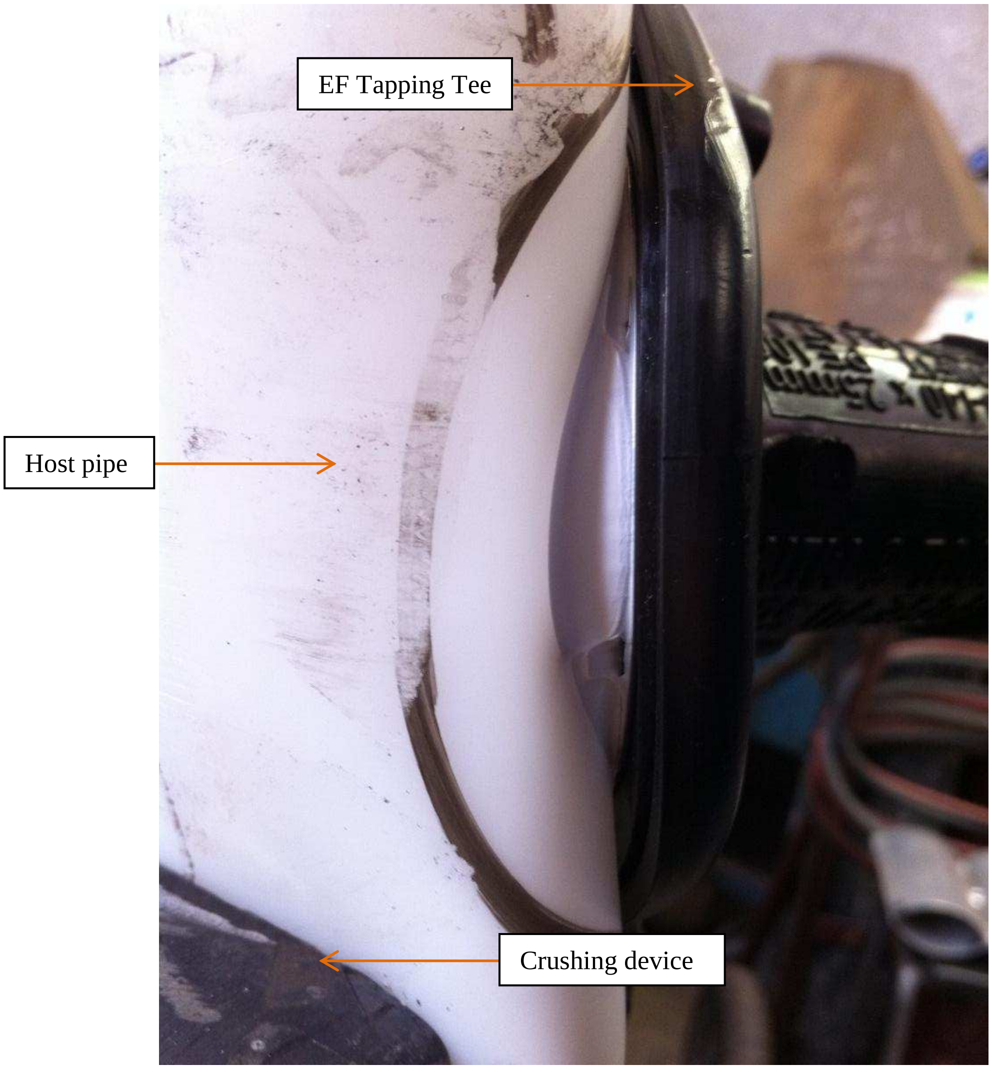

Fig. 4 Post-crush of ‘perfect’ specimen

ULTRASOUND EXPERIMENT

A rig was designed and built to observe the leak paths of failed joints. The rig consisted of an ultrasonic focussing lens attached to a stepper motor stage (**Fig. 5**). The stepper motor stage allowed for line scans to be performed. Joints that have been tested to failure in the fatigue programme (**Fig. 2**) were cut in half using a bandsaw, along the centre line of the pipe. This left the internal bore and the underside of the tapping tee exposed so that the ultrasonic transducer could focus on the internal bore of the pipe. Furthermore, the focussing lens transmitted pulses perpendicular to the internal bore of the PE pipe and fitting assembly.

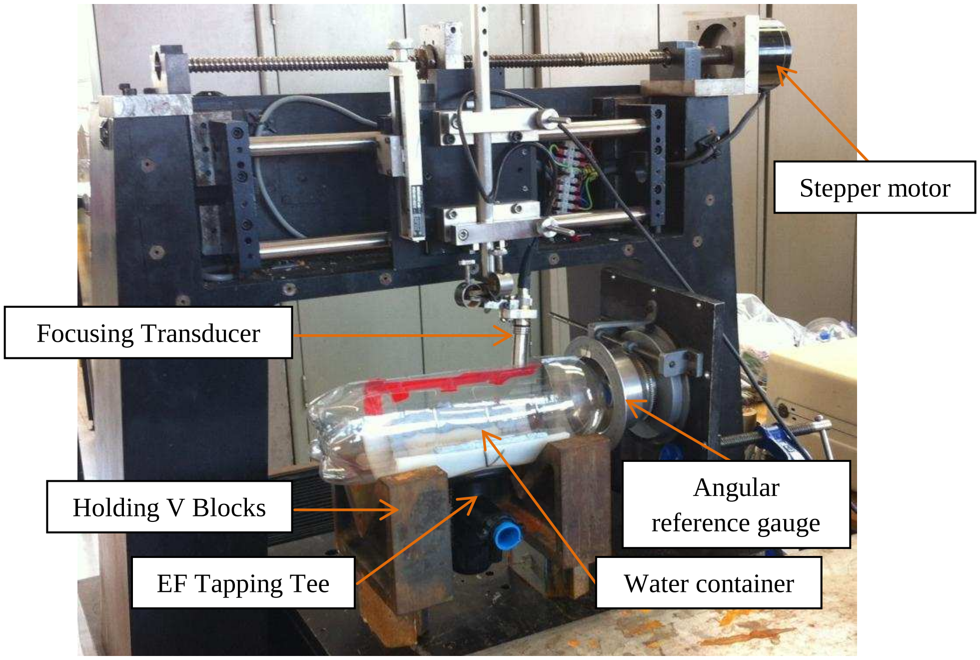

Fig. 5 Ultrasound focussing transducer arrangement

Preliminary line scans were conducted on the internal bore of the pipe in order to observe the delaminated surface of the fusion interface. The line scans were then knitted together to create a map of the fusion zone thus observing the leak path (Fig. 6).

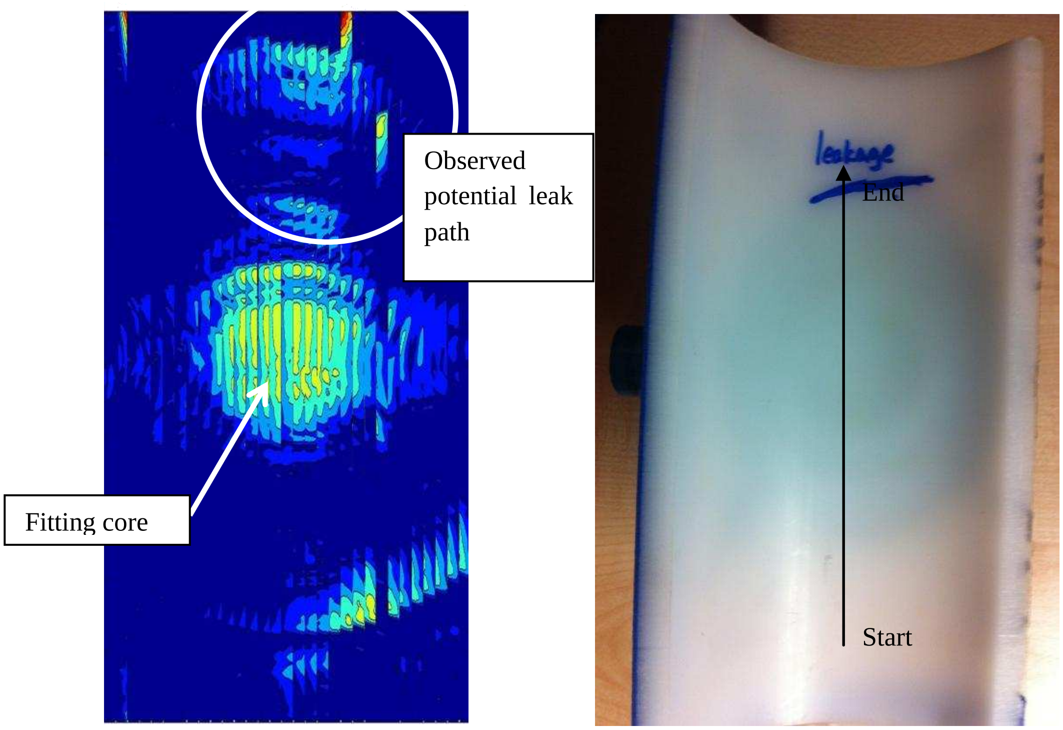

Fig. 6 Preliminary line scan results showing leak path (Left) and scan direction (right)

Once the map was created, the predicted leak path was confirmed by applying a flow of water through the EF tapping tee fitting. This was achieved using a basic hand pump.

Following on from the degree of success with single transducer ultrasonic analysis, a bespoke ultrasonic sensor array was designed and built to monitor the crack propagation during a live fatigue test. The aim of the experiment was to observe crack growth of EF tapping tees whilst they are subject to a pressure fatigue test. The outcomes of this experiment will be shown at the conference.

DISCUSSION AND CONCLUSIONS

There is a dramatic decrease in joint performance when EF tapping tees are subject to contamination prior to the welding process. It is clear from **Fig. 2** that if the jointing interface were to be contaminated, failures associated with fatigue can occur in a relatively short space of time. It should be noted that the pressure amplitudes used in the fatigue test were aimed to replicate the pressures that may be expected in surge events. However, the frequency of the pressure ranges are slower than a surge, as the frequencies used were between 0.007 – 0.016 Hz (90% to 40% $P_{mat,\ max}$ respectively). The predictability of failure also becomes more difficult as the pressure range decreases – this was evident due to the increase in scatter as the pressure range was reduced.

It is interesting to note that the destructive tests showed a visually distinct difference in mechanical failure if the joint were to be subject to a talc contaminant prior to welding. With regards to the specimen subject to contamination (**Fig. 3**), there was evidence to suggest that a bond was beginning to form. Some filament wires were still present once the fitting was removed from the host pipe. This suggests that the filament wire may have been providing some degree of structural strength to the joint assembly which may let the fitting pass the initial pressure test before it is put in service. However, the joint would still fail in a brittle manner if it were subject to the fatigue testing regime.

The leak path investigation using non-destructive ultrasonic methods showed promising preliminary results. Being able to observe the directions of which the leak paths (cracks) have formed gives an insight into the failure mechanics of the fitting. Furthermore, in principle this can be confirmed using the same methods but during the live fatigue test.

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