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DEVELOPMENT OF FLAW ACCEPTANCE CRITERIA FOR WELDED JOINTS IN PE PIPES

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ABSTRACT

There are a number of non-destructive testing techniques currently being promoted for the inspection of butt fusion and electrofusion joints in polyethylene (PE) pipes. Depending on the technique and inspection procedure, various types of flaw, including discrete planar lack of fusion, particulate contamination, voids, cold fusions and pipe under-penetration can be detected. However, the usefulness of these techniques is limited due to the fact that there are currently no acceptance criteria available for the size or concentration of any detected flaws. Some work is being carried out in ASME in the US to use the same fracture mechanics approach that is used for metals to predict the critical sizes of lack of fusion flaws and voids. However, since polyethylene is very ductile, this methodology is not suitable for this material and the results will be very conservative. In addition, this approach is not applicable to either particulate contamination or cold fusions.

This paper presents a methodology for determining flaw acceptance criteria in PE pipe joints using experimental data from mechanical testing, by comparing the results on joints containing flaws of known size or concentration with results on unflawed joints. With this approach it is important that the mechanical tests used are sufficiently discriminating to be able to distinguish between flawed and unflawed joints. For this reason, this paper also describes work that has been carried out to compare different mechanical tests on both butt fusion and electrofusion joints in PE pipes in order to determine which tests are the most suitable for determining flaw acceptance criteria.

INTRODUCTION

TWI has been carrying out research into non-destructive testing (NDT) of welded joints in PE pipes for over 30 years (1-16) and has recently developed a phased array ultrasonic testing (PAUT) system that can detect every type of embedded flaw in both butt fusion and electrofusion joints in PE pipes, including voids, lack of fusion, particulate contamination and cold welds (1-6). However, before any NDT system can be used to accept or reject a welded joint, the flaw acceptance criteria must be defined.

The acceptance criteria for planar and volumetric flaws in welded joints in structural materials are normally based on linear elastic fracture mechanics (LEFM), where the stress perpendicular to an infinitely sharp crack is given by:

$$\sigma = \frac{K}{(2\pi r)^{1/2}}$$

where r is the distance from the crack tip and K is the stress intensity factor.

The above equation predicts an infinite stress at the crack tip (r = 0). However, in reality, materials develop plastic strains when the yield strength is exceeded, which blunts the crack (17). For most metals and some brittle plastics it can be assumed that the amount of yielding at the crack tip is very small and the amount of plastic deformation is restricted by the surrounding material, which remains elastic during loading.

However, very tough polymers, such as PE pipe grades, produce very large plastic zones due to crazing, which exceed the stress field around the crack tip. The relaxation of the crack tip stresses caused by this yielding phenomenon compromises the validity of the LEFM theory for these materials (18), which implies that the elastic stress analysis becomes increasingly inaccurate as the plastic region at the crack tip becomes larger and LEFM is no longer useful for predicting critical flaw sizes (19).

An alternative method for determining flaw acceptance criteria in welded PE pipe joints, which has been employed at TWI, is to use an empirical approach where joints containing known flaws are mechanically tested and the results are compared with tests on unflawed joints.

TYPES OF FLAWS IN PE PIPE JOINTS AND FLAW INSERTION PROCEDURES

In 2010 TWI sent out a questionnaire to European companies involved in the manufacture or installation of plastics pipes in order to determine what the main types of flaw were of concern to the industry. A total of 72 responses from ten countries were received and the results are shown in Figure 1, which reveals that the flaw of most concern to the industry is the cold weld, which is where there is incomplete diffusion of the PE molecules across the weld interface during welding, due to inadequate temperature or time, which results in a brittle failure mode when mechanically tested. The other main flaw types, according to the responses from the questionnaire, were:

- Fine particulate contamination, due to airborne dust;
- Pipe under-penetration in electrofusion (EF) joints, which is often due to not clamping the pipes during the welding process;
- Planar flaws, due to such things as fingerprints, grease, perspiration or rain droplets getting into the joint;
- Coarse particulates, due to sand, grit or mud.

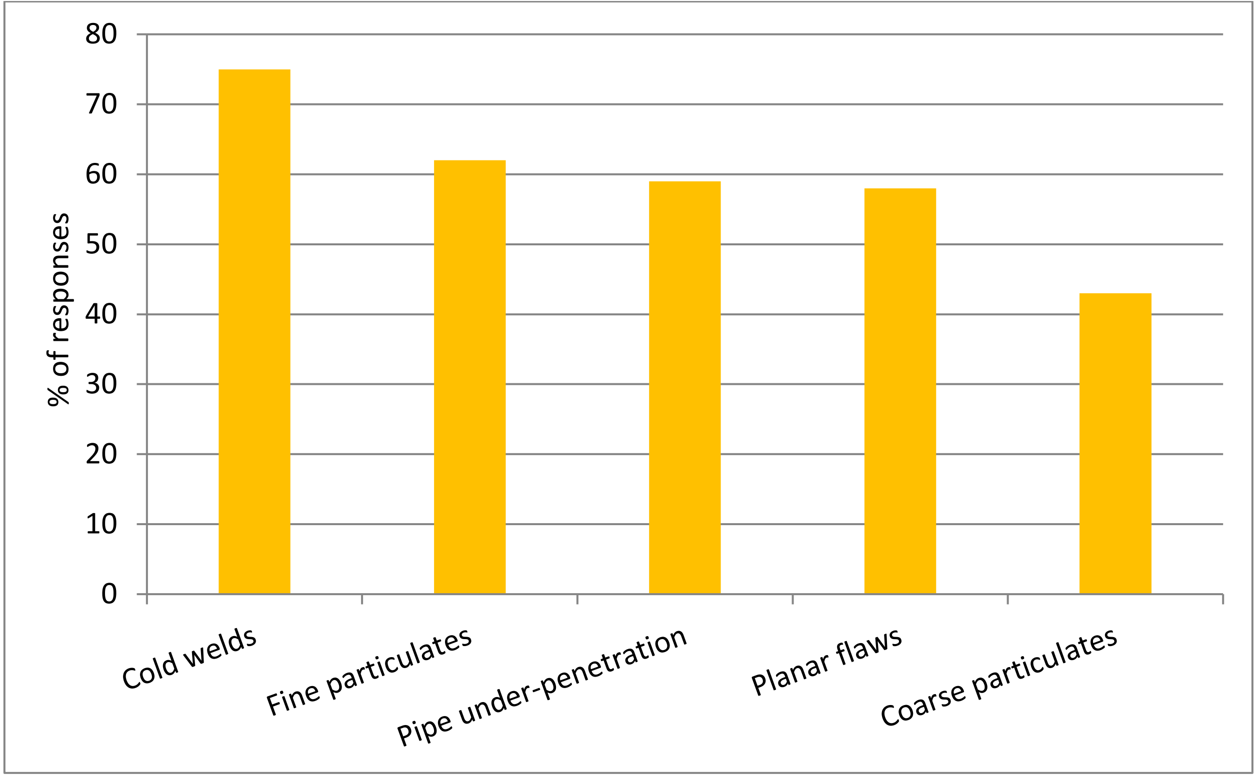

Figure 1: Results of industry questionnaire on main types of flaw possible when welding PE pipes in the field.

It should be noted that none of the above flaws can be detected consistently by visual examination of the joint, which is why there is a need for volumetric NDT.

In order to determine the flaw acceptance criteria (critical flaw sizes or particulate contamination/cold weld levels that reduce the integrity of the joint) from mechanical tests, it is necessary to know the actual size of the planar flaw or the actual quantity of particulate contamination in the joint. For this reason, TWI has developed procedures for inserting idealized simulations of actual flaws into butt fusion and EF joints in PE pipes.

Fine particulate contamination was simulated using micronized talc, with a particle size < 45µm, which was inserted into butt fusion joints by applying it to the trimmed pipe end using a soft-haired brush and into EF joints by applying it to the scraped pipe surface using a rubber roller (20). Coarse particulate contamination was simulated using graded silica sand, with a particle size between 150 and 300µm, which was attached to the end of the pipes to be joined by placing them in a fluidized sand bed (3).

In order to quantify the actual percentage area of the joint contaminated, specimens were cut from the welded joint and analysed using micro computed tomography (µCT). This technique produces two- and three-dimensional images of an object, showing characteristics of its internal structure. Figure 2 shows a specimen from a contaminated butt fusion joint and a virtual section through the weld interface, from which the percentage area of contamination can be quantified using image analysis software.

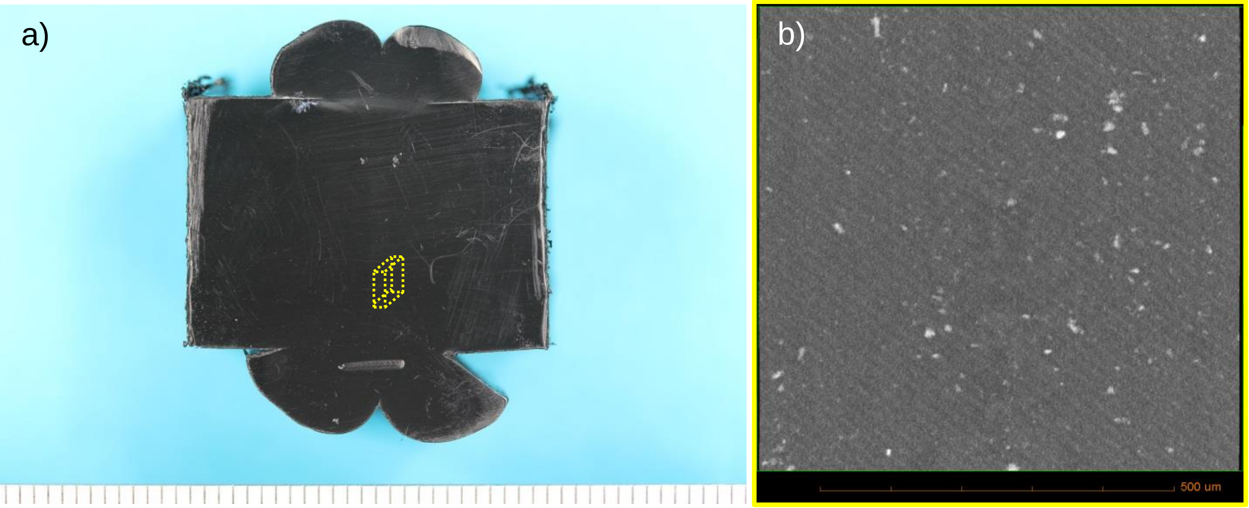

Figure 2: a) Butt fusion specimen containing particulate contamination, and b) virtual section through a µCT tomograph of the specimen at the position shown by the yellow cuboid in a).

Planar flaws were simulated using 25µm thick aluminium discs, which were heat staked to either the trimmed pipe end, for butt fusion joints, or the scraped pipe surface, for EF joints (21). Aluminium discs were used because, for ultrasonic NDT, they are a good simulation of actual planar flaws and do not deform during the welding process (13).

FLAW ACCEPTANCE CRITERIA METHODOLOGIES

PE pipe joints have to survive both the service conditions, which involves long-term loads, and pipeline installation, which involves short-term loads. It is therefore important that the effect of flaws on both the long-term and short-term integrity of the joints is assessed.

Long-term Integrity

A procedure used at TWI to determine critical flaw sizes and particulate contamination levels for long-term integrity is to carry out long-term mechanical tests at elevated temperature that generate slow crack growth in joints containing flaws of known size or quantity and also on joints containing no deliberate flaws.

For unflawed butt fusion joints subjected to a constant tensile load at elevated temperature, such as in the whole pipe tensile creep rupture test according to Annex B of BS EN 12814-3 (22), slow crack growth will initiate from the notch between the weld bead and the pipe surface and will then propagate radially through the pipe wall (Figure 3).

Figure 3: Typical failure of an unflawed butt fusion joint in PE pipe when subjected to a constant tensile load at elevated temperature, showing failure initiating from the notch between the weld bead and the pipe wall.

However, if there is a critical flaw in the joint, the failure will be through the weld interface (Figure 4). The flaw acceptance criterion for long-term performance of butt fusion joints in PE pipes can therefore be defined as the minimum size of lack-of-fusion flaw or minimum concentration of particulate contamination that causes the failure to propagate through the weld interface.

The above definition can also apply to EF joints, since unflawed joints subjected to a constant tensile load at elevated temperature will fail due to slow crack growth through either the pipe wall or coupler, initiating from either the internal or external cold zone notch (Figure 5), whereas, if there is a critical flaw in the joint, the failure will be through the weld interface and the pipe will shear out of the EF fitting (Figure 6).

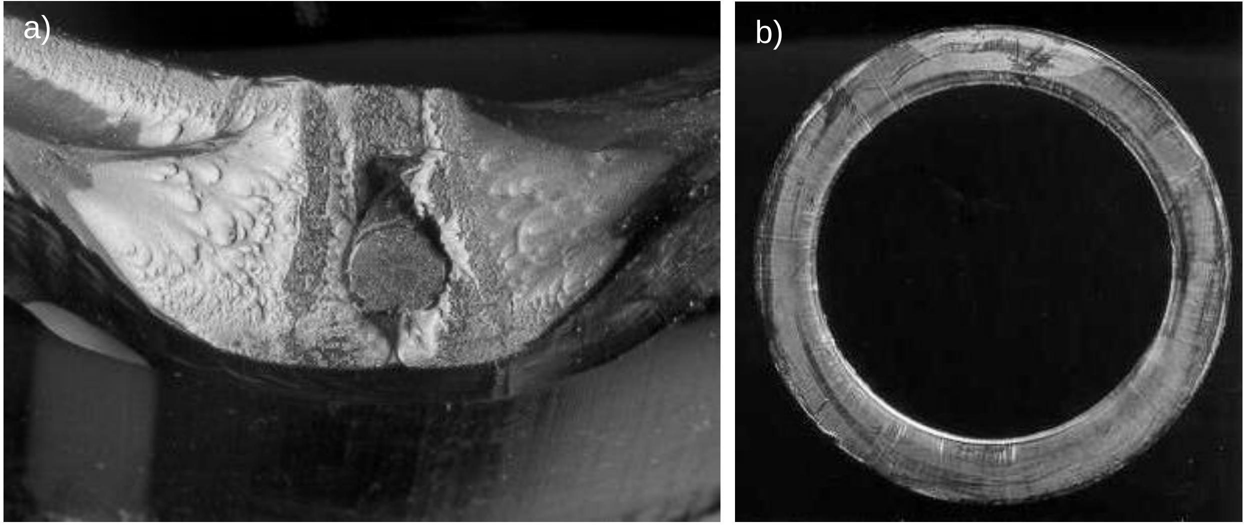

Figure 4: Typical failures of butt fusion joints in PE pipe containing critical flaws when subjected to a constant tensile load at elevated temperature, showing failure through the weld interface: a) containing a planar lack-of-fusion defect; b) containing fine particulate contamination.

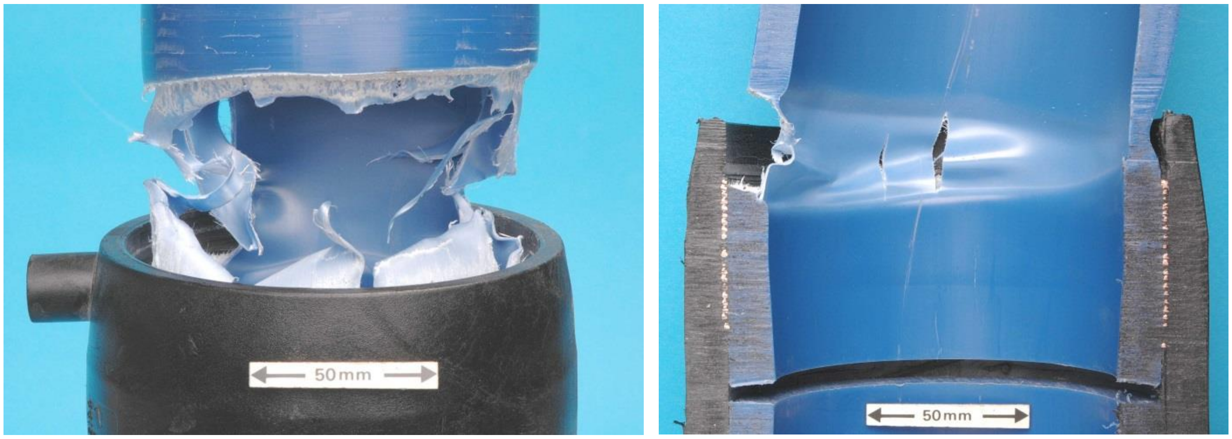

Figure 5: Typical failure of an unflawed EF joint in PE pipe when subjected to a constant tensile load at elevated temperature, showing failure initiating from the external cold zone notch between the pipe and fitting.

It should be noted that, since the resistance to slow crack growth of the weld interface may well depend on the PE resin and the welding procedure used, the critical flaw size and contamination levels will probably be dependent on these variables.

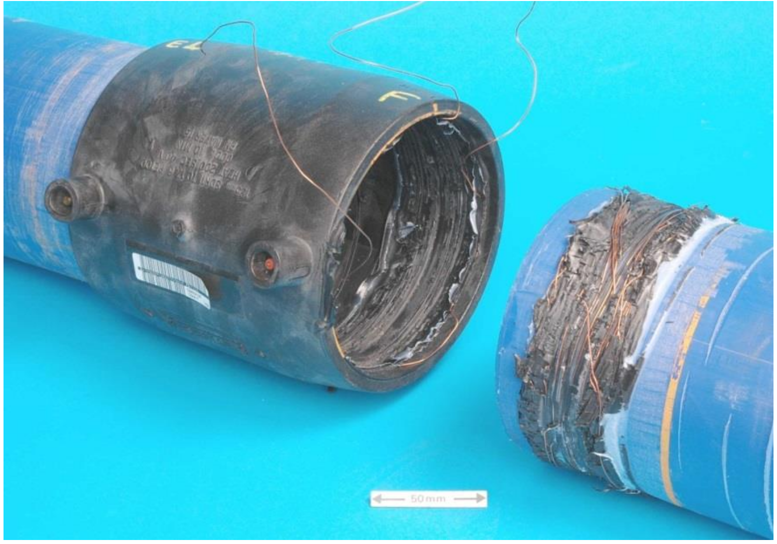

Figure 6: Typical failure of an EF joint in PE pipe containing a critical level of pipe under-penetration when subjected to a constant tensile load at elevated temperature, showing failure through the weld interface.

Short-term Integrity

The procedure used at TWI to determine critical flaw sizes and particulate contamination levels for short-term integrity is to generate graphs of a relevant short-term property against flaw size or contamination level, as shown in Figure 7.

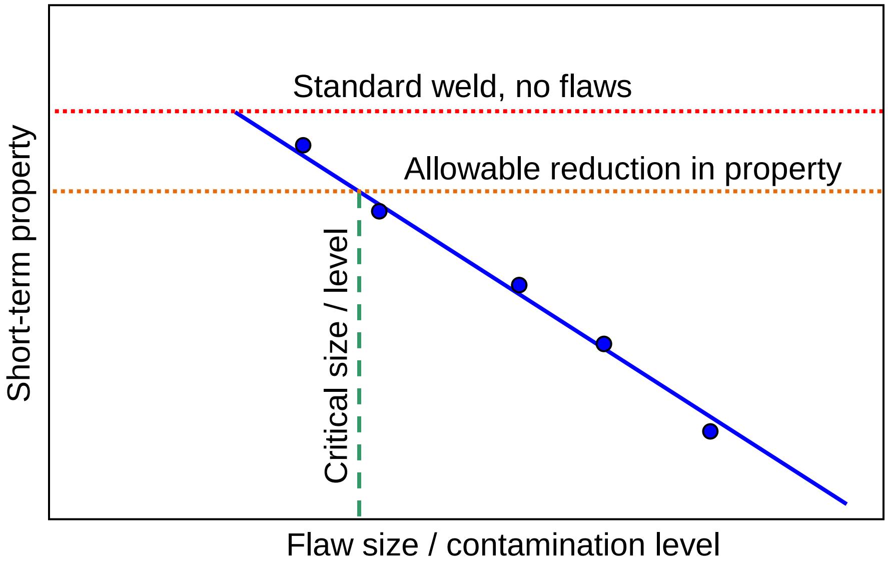

Figure 7: Schematic of a graph used to determine critical flaw sizes or contamination levels for short-term joint integrity.

An allowable reduction in the short-term property compared to an unflawed “perfect” weld is either agreed or defined in the relevant standard or specification, which then allows the critical flaw size or particulate contamination level to be determined.

Using this methodology, it is important that the chosen short-term mechanical test provides a property that changes significantly with the size of the flaw or level of contamination, i.e. generates data with a steep slope in Figure 7.

The results from a number of different short-term mechanical tests on butt fusion joints, including: three-point bend tests, tensile tests with dog-bone and waisted specimen geometries, and Charpy impact tests, were compared by Hinchcliffe and Troughton (23). The results suggested that the three-point bend test and the tensile test using a dog-bone specimen geometry are very poor at discriminating between different qualities of butt fusion joint, since neither of these tests generated any failures in the joint itself. The most discriminating test was found to be a tensile test using a waisted test specimen, such as that defined in ISO 13953 and EN 12814-7, which is designed to ensure that failure occurs at the weld rather than in the parent pipe. In addition, the energy to break the specimen was found to be the best parameter for distinguishing between different qualities of weld.

More recently, work has been carried out at TWI to compare the results from the tensile test using a waisted test specimen with those from the high speed tensile impact test, as defined in ASTM F2634 (24), on butt fusion joints in PE pipes containing fine particulate contamination. An example of the results is shown in Figure 8.

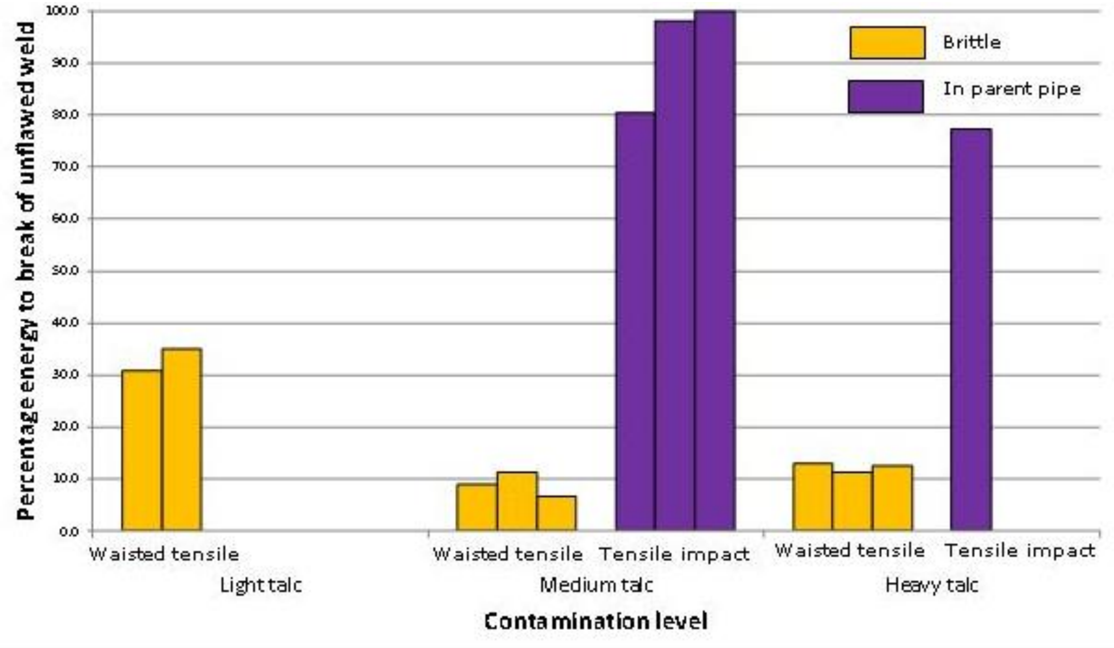

Figure 8: Energy to break waisted tensile test and high speed impact test specimens from talc-contaminated butt fusion joints in 180mm SDR17 PE80 pipe as a percentage of the energy to break specimens cut from butt fusion joints containing no flaws.

The above results show that even light loadings of fine particulate resulted in a reduction in the energy to break the waisted tensile test specimens by around 70% compared to butt fusion joints containing no deliberate flaws, which increased to around 90% for higher loading. In addition, all of the contaminated joints failed in a brittle manner, whereas the unflawed joints all failed in a ductile manner. The results for the high speed tensile impact tests, however, showed that, even for a heavy loading of talc, the specimens still failed in a ductile manner in the parent pipe. Although no high speed tensile impact tests were carried out on joints containing a light loading of talc, it would be expected that these would also fail in the parent pipe.

The results from a number of different short-term mechanical tests on EF joints were compared by Troughton et al (20) and the results showed that a peel decohesion test, such as defined in ISO 13954 or EN 12814-4, was very good at discriminating between different qualities of EF joint.

CONCLUSIONS

It is suggested that, until a proven fracture mechanics technique has been verified for assessing the significance of flaws in welded joints in PE pipes, the most appropriate method for determining flaw acceptance criteria is an empirical approach where the results of short-term and long-term mechanical tests on joints containing planar flaws of different size or particulate flaws of different concentrations are compared with the results of mechanical tests on unflawed joints. Using this methodology, it is very important to ensure that the mechanical tests chosen to determine the flaw acceptance criteria are able to distinguish between flaws of different size/concentration.

The work described here suggests that the most appropriate short-term test for determining flaw acceptance criteria in butt fusion joints is a tensile test using a waisted test specimen geometry, where the cross-sectional area is a minimum at the joint line, and the most appropriate parameter is the energy to break the specimen, and a suitable short-term test for EF joints is a peel decohesion test. The recommended long-term test for determining flaw acceptance criteria is the whole pipe tensile creep rupture test.

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