JOURNAL OF MATERIALS SCIENCE 27 (1992) 2807–2810

# Novel approach to the impact testing of butt fusion-welded joints

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Charpy impact tests have been carried out on specimens removed from the joint region in butt fusion-welded polyethylene pipe. In order to ensure that crack initiation occurs precisely at the weld line, a novel method of notching has been used. $G_c$ data have been derived from these tests, which were conducted at temperatures of $-150$ and 23 °C. Results obtained from pendulum impact and instrumented falling weight tests show consistent differences, probably attributable to the speed of impact. Data have also been obtained for the parent unwelded material.

## 1. Introduction

Polyethylene (PE) is used extensively as a material for gas, water and effluent pipelines and one of the more common fabrication methods is butt fusion joining or welding. As the in-service life of a pipeline system may be at least 50 years [1], it is vital that any joints so produced remain serviceable throughout this time period. Accordingly, a knowledge of the fatigue and fracture properties of both the pipe material and the associated joints is very important.

Non-destructive testing (NDT) techniques for welded joints are still limited [2] and therefore reliance is placed either on the operator to produce good joints or on the use of automatic machines to build in joint quality [3]. Destructive tests, involving detailed microstructural examination of welds can be helpful in the interpretation and optimization of weld-line integrity, as derived from tensile strength measurements. However, there is still no consensus of opinion on the most effective testing methods particularly for short-term tests [4]. In the particular case of impact tests on welded joints, the results often depend on the skill of the operator at notching the specimen precisely at the weld line.

In order to develop a sound rational understanding of the butt fusion-welding process, it is vital to establish methods that truly test the behaviour of the welded area. The availability of such data is comparatively rare. The mechanical properties of the weld will be very dependent on the localized morphology, which, in turn, will be a function of the processing conditions used to form the joint. The establishment of innovative testing strategies provides the prospect of a deeper understanding of this welding technique.

In the general context of short-term testing, the application of linear elastic fracture mechanics (LEFM) could provide basic fracture data from impact tests, provided a sharp crack is incorporated in the specimen [5, 6]. Specifically in the study reported in this paper, the aim was to use a novel method of introducing a notch into the welded specimens at the time when the joint was produced. This should ensure that the initial failure of the specimen occurs at the weld interface, rather than merely somewhere in the region of the weld. The method used for producing the sharp notches is described. Also, we report the critical strain energy release rate, $G_c$, derived from both pendulum and instrumented falling weight impact tests (IFWIT) conducted on the welded and parent material.

## 2. Experimental procedure

### 2.1. Specimen preparation

A BP Rigidex PC002-50 R968 pipe grade PE resin in the form of 125 mm SDR 11 pipe was used for this research. Lengths of pipe were joined by butt fusion using a micro-processor-controlled Fusion Group plc. (Chesterfield, UK) automated butt fusion machine. The welding conditions used were standard for the pipe size and material (see Table I).

Sharp notches were introduced into half of the welds by placing lengths of PTFE tape (12 mm wide and 0.075 mm thick) into the joint, after trimming of the pipe ends had been completed and before the heater plate was inserted (Fig. 1). PTFE was used because it should not adhere to the heater plate or to

TABLE I Joining conditions

| | |
|---|---|
| Heater temperature (°C) | 205 |
| Initial pressure (bar) | 10* |
| Heat soak (s) | 120 |
| Welding pressure (bar) | 10* |
| Welding time (s) | 600 |

* Machine pressure.

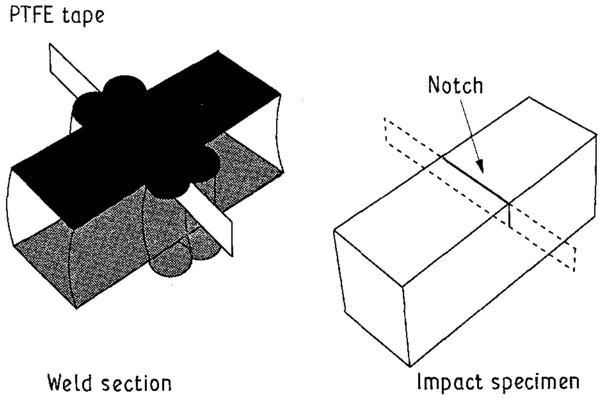


*Figure 1* Schematic diagram showing the method of notching.

the pipe faces thus ensuring that a sharp notch was produced at the weld interface.

Charpy impact specimens for both pendulum and IFWIT testing were produced by initially cutting strips from the pipe wall and then machining them to a uniform rectangular bar with the dimensions 120 mm × 14.5 mm × 10 mm. The specimens were cut so that the weld was in the centre of the bar (Fig. 1) and a strip of PTFE tape remained at one edge of the weld to act as a notch for the impact testing. Notch depths were varied to allow a range of impact energies to be achieved during testing, therefore enabling a $G_c$ value to be established. In addition to the PTFE notched specimens, a number of test pieces were machined from the unwelded pipe and notched with a razor blade for a comparison of results. Once again a range of notch depths was used. Samples containing PTFE and razor notches were sectioned and their root tip radii measured to ensure that they were comparable.

## 2.2. Impact testing

IFWIT was carried out using a Rosand IFWIT machine set up with a Charpy striker and having a span of 70 mm (Fig. 2). A 5 kg weight with a drop height of 0.815 m was used to give an impact velocity of 3.9 m s$^{-1}$. All 26 specimens (13 welded specimens with a PTFE notch and 13 razor-notched parent material) were tested at room temperature and − 150 °C. In all cases a load/deflection curve was recorded for each specimen.

Conventional Charpy pendulum impact tests were conducted according to BS 2782 using CEAST impact testing apparatus with a 4J hammer giving an impact velocity of 2.9 m s$^{-1}$. As with the IFWIT, 26 specimens were used (13 PTFE and 13 razor notched) and an impact energy was recorded for each.

For both test methods, the notch depths were measured using a travelling microscope after the specimens had been tested and then a value of impact strength was calculated from

$$\text{impact strength} = \frac{\text{fracture energy}}{\text{area at notch section}}$$

After impact testing, a selection of the samples were sputter coated with gold for investigation of the fracture surfaces in the scanning electron microscope (SEM).

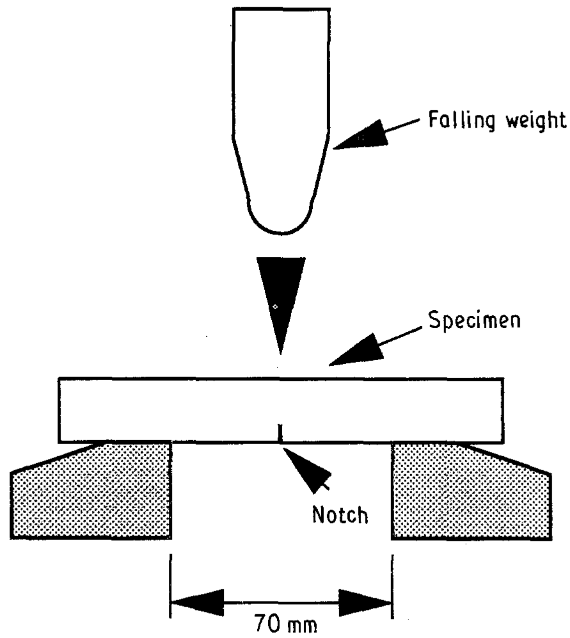


*Figure 2* Specimen arrangements used during the instrumented falling weight impact testing.

## 3. Fracture mechanics analysis

To derive values of $G_c$, the critical strain energy release rate, a LEFM approach was used. The specimen is assumed to deform macroscopically in an elastic manner, such that the compliance of the specimen, $C$, is a function of its geometry and crack length, $a$. Hence for a load, $P$, with a deflection of $x$, we have

$$\frac{x}{P} = C(a) \tag{1}$$

As the deformation is elastic, the energy absorbed by the specimen, $W$, is the area under the load deflection curve, i.e.

$$W = \frac{Px}{2} \tag{2}$$

and hence from Equation 1 we have

$$W = \frac{CP^2}{2} \tag{3}$$

and for fracture

$$W_c = \frac{CP_c^2}{2} \tag{4}$$

where $W_c$ and $P_c$ are the critical work done and load, respectively. For a specimen of thickness $B$, the critical strain energy release rate, $G_c$, is given by

$$G_c = \frac{1}{B}\frac{dW_c}{da} \tag{5}$$

but

$$\frac{dW_c}{da} = \left(\frac{dW_c}{dC}\right)\left(\frac{dC}{da}\right) = \frac{P_c^2}{2}\frac{dC}{da} \tag{6}$$

$$G_c = \frac{P_c^2}{2B}\frac{dC}{da} \qquad (7)$$

however

$$P_c^2 = \frac{2W_c}{C} \qquad (8)$$

therefore

$$G_c = \frac{W_c}{BC}\frac{dC}{da} \qquad (9a)$$

or

$$G_c = \frac{W_c}{BD\phi} \qquad (9b)$$

where $\phi = C/[dC/d(a/D)]$ where $D$ is specimen width. Thus the energy at fracture, $W_c$, can be plotted as a function of $BD\phi$ for a range of specimen geometries to determine a value for $G_c$.

## 4. Results and discussion

The notch tip radii of both the PTFE and razor blade methods were found to be of a similar order (5 and 2 μm, respectively) and therefore suitable for comparisons to be drawn between the two sets of data. A number of test variables were found to affect the consistency of the test results; initial notching and specimen alignment in the test rig in particular. Data from the PTFE notched specimens were more scattered perhaps due to the inconsistent notch depth across the specimen. The impact energy has a strong dependence on the initial crack length, the energy decreasing as crack size increases (Fig. 3) with the unwelded parent material specimens giving higher values than their welded counterparts. Values produced by the two test methods gave the same trends. However, those from the IFWIT method were slightly lower than those from pendulum impact testing. This may be due to the different loading rates between the two methods, the pendulum impact being slower than the falling weight. This may also explain the fact that during pendulum impact tests, none of the specimens tested at 23 °C broke completely, but bent around the striker as the crack progressed through the test-piece.

The experimental $G_c$ values were obtained from $W_c = G_c BD\phi$ by plotting the impact energy absorbed, $W$, against $BD\phi$ (Fig. 4). The gradient of the resulting plot is $G_c$. For a three-point bend test configuration, as used in Charpy impact and IFWIT methods, the geometric factor, $\phi$, is given by [5]

$$\phi = \frac{1}{2}\left(\frac{a}{D}\right) + \frac{1}{18\pi}\left(\frac{s}{D}\right)\frac{1}{(a/D)} \qquad (10)$$

where $s$ is the span used in the three-point bend test configuration.

As seen in Fig. 4, there is a linear relationship between $W_c$ and $BD\phi$ allowing evaluation of $G_c$ values. The scatter of the data is moderate with an excellent degree of fit for the data from the unwelded specimens. The $G_c$ values obtained are shown in Table II and it can be seen that the parent material has

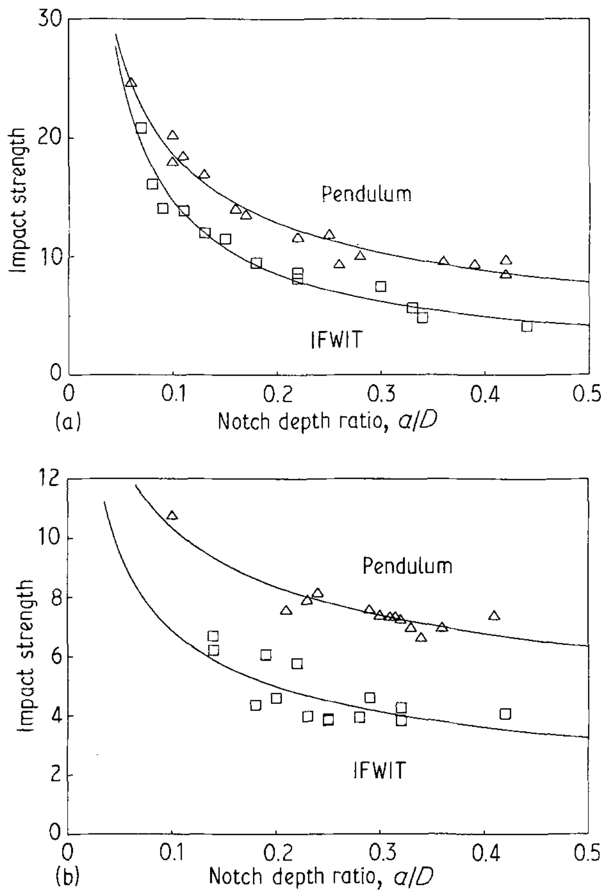


*Figure 3* Measured impact strength versus notch depth ratio for (a) parent PE, and (b) welded PE.

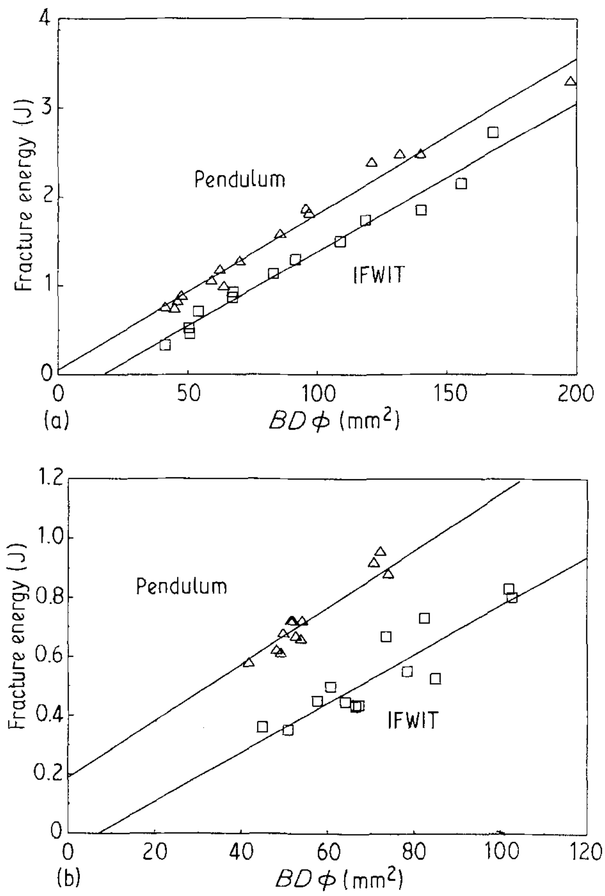


*Figure 4* Fracture energy, $W_c$, versus $BD\phi$ for (a) parent PE, and (b) welded PE.

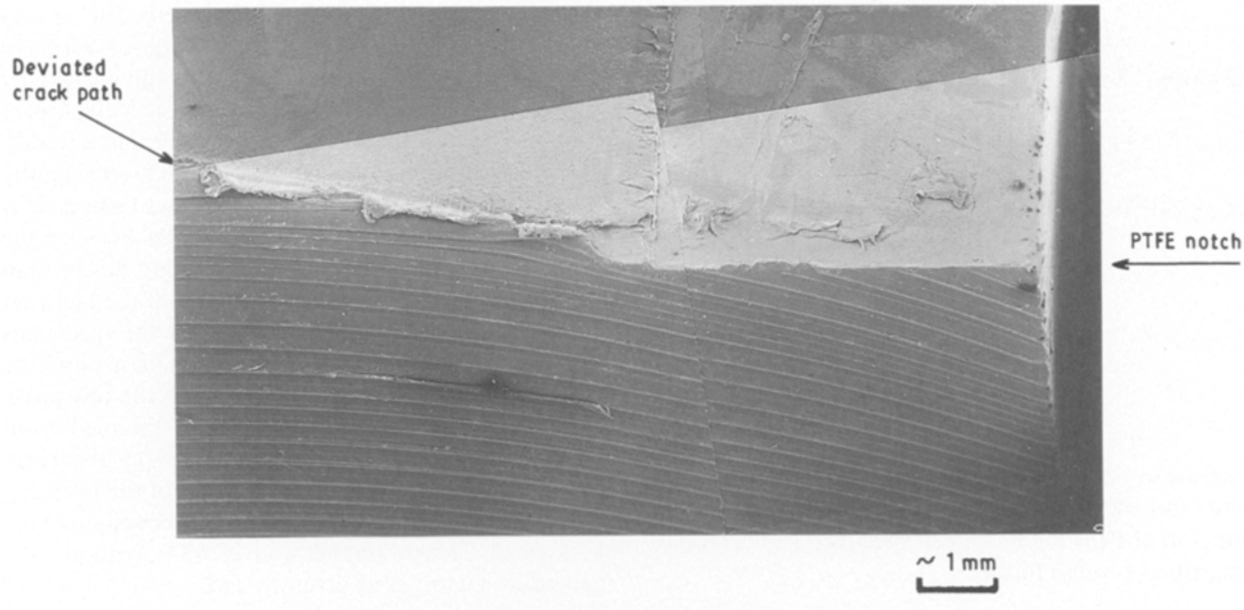


*Figure 5* Scanning electron micrograph of fracture surface having a PTFE notch.

a higher value of $G_c$ than the welded specimens for both test temperatures used.

An investigation of the fracture surfaces shows that the majority of the cracks although starting on the weld interface and running in the impact direction, deviated from the weld line and quickly moved into the parent material. This is seen in Fig. 5, which shows a scanning electron micrograph of a fracture surface produced at a test temperature of 23 °C. It is interesting that failure does not occur across the whole of the weld zone. The deviation of the crack from the weld interface implies local inhomogeneities in the microstructure either side of this interface. In fact, a detailed investigation of the complete microstructure of a whole range of pipe welds has been undertaken [7] and the studies provide an explanation for these fracture data.

The cracks produced during pendulum impact tests are most likely to remain on the weld interface, this possibly being due to the slower impact speed used. The fracture surfaces exhibit large areas of fast crack growth (flat brittle appearance) followed by a short deceleration phase (a more banded ductile surface). In the unwelded samples, the deceleration phase is larger and banded across its width due to its greater ductility and hence higher fracture resistance.

## 5. Conclusion

A LEFM approach can be used to obtain realistic and consistent $G_c$ data from impact tests on butt fusion-welded PE pipe specimens.

The use of PTFE tape as a means of notching the impact specimens proved highly successful as a method of obtaining $G_c$ values for a weld. Comparisons of these values with those of unwelded razor-notched specimens are good, with little evidence to suggest that their differing crack tip radii significantly affect the $G_c$ values.

The $G_c$ values obtained by experiment are reasonably consistent for the two different testing methods used. The higher impact energy values obtained from the pendulum test may be accounted for by the greater impact velocity and frictional losses, caused by the sample folding on impact. The IFWIT method is preferable to conventional pendulum tests for evaluation of impact energy because it provides much more information on the impact event.

TABLE II $G_c$ values

| Specimen | Temperature (°C) | $G_c$ (kJm$^{-2}$) | |
|---|---|---|---|
| | | IFWIT | Pendulum |
| MDPE: welded | 23 | 7.8 | 10.7 |
| unwelded | | 16.2 | 17.5 |
| welded | − 150 | – | 4.8 |
| unwelded | | – | 7.2 |

## Acknowledgements

The authors thank the SERC and The Welding Institute for supporting this work and particularly for the provision of a studentship for J. Haunton. We are also grateful to Wavin Industrial Products Ltd for provision of pipe materials.

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*Received 2 September*
*and accepted 10 September 1991*