AN INTERIM APPROACH TO DETERMINE DYNAMIC DUCTILE FRACTURE RESISTANCE OF MODERN HIGH TOUGHNESS PIPELINE STEELS

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ABSTRACT

The ductile fracture toughness of steel is used to assess the ability of a pipeline to resist long running ductile fractures in a burst event. In modern low carbon clean steels with high toughness, conventional measures of ductile fracture toughness (standard Charpy and DWTT energy) are under review, and alternatives are being studied. The major factor causing concern is the inability of these tests to isolate the energy associated with crack propagation from the total energy absorbed during the specimen fracture. This is significant in modern high toughness steels because their initiation toughness is extremely high.

To resolve crack propagation energy, a novel modification was evaluated for both Charpy and DWTT specimens by employing a back-slot including a snug fitting shim to replace the removed material. In most cases, this modification was effective in curtailing the load-displacement trace when the propagating crack interacted with the slot on the backside of the specimen, without affecting the initial portion of the trace; this allowed crack propagation energies to be resolved. The propagation energy determined by this method is compared with the total energy and conventional test parameters. The crack propagation energy values inferred based on this should be validated, in future burst test.

INTRODUCTION

Design against long ductile fracture propagation in gas pipelines involves an analysis of the balance between driving force derived from the gas pressure, and the fracture resistance of the material. Initially, the shelf energy in the Charpy test was successfully used as a measure of fracture propagation resistance. As material strength, pipe diameter and operating pressure increased, requiring greater fracture propagation resistance, the limitations of the Charpy energy approach became increasingly apparent[4]. This is because for modern steels, the Charpy test involves significant energy absorption contributions from processes not related to fracture propagation. Various attempts have been made to extend the range of applicability of the Charpy energy, and to develop alternative approaches more directly related to the propagation process. If an energy-balance approach is to be maintained, and if material resistance is to be measured in a fairly simple laboratory notch bend test (e.g., Charpy or drop-weight tear), the problem reduces to the isolation of the propagation energy absorption per unit of crack advance. The suppression of initiation energy in the DWTT by the use of alternative notching techniques appears to offer some benefit[5]. Some researchers, on the other hand, have attempted to isolate the propagation energy by varying notch depth, but this raises the potential complication of the mechanical dissimilarity in the initiation process between specimens of different notch depth[6]. In the present investigation, the potential for measuring specific propagation energy by introducing back slots of varying depth was investigated. By filling the back slot with a shim, an identical initiation process can be maintained while the ligament length is varied.

STEEL CHARACTERIZATION

The majority of the steels investigated in this program were modern, controlled-processed, high-toughness X70 and X80 materials. The exceptions were an X52 and an X100 material, included to extend the range of applicability of the investigation. Table 1 lists the Grade and dimensional information on the pipes. A wide range of wall thickness and pipe diameters is included in the selection.

Small tensile specimens (gauge diameter of 5 mm and gauge length of 25 mm) were extracted, in the circumferential orientation and tested at a quasi-static rate (0.0001 s⁻¹) and a higher rate (2 s⁻¹).

The results showed the following effects from increased strain rate:

- The yield strength increase with strain rate is more pronounced for some steels than others. Similar observations can be made for the tensile strength.
- The drop in the strain to fracture (εf) with increased strain rate is small.
- The strain energy density obtained from the area under the true stress-strain curve to fracture had a similar trend to that displayed by εf.
Charpy V-notch testing was performed with the objective of determining the ductile fracture behaviour in the service temperature range. Steel 9, (the X52 grade) was the only material that had specific energy less than 1.27 J mm\(^{-2}\) (600 ft-lb in\(^{-2}\)) at room temperature. Steels 6, 7, 8, and 10 displayed clear indications of RUS behaviour, i.e., as the test temperature increased the number of splits decreased with corresponding increase in the total absorbed energy. Table 2 presents summary results.

<table>
<thead>
<tr>
<th>No.</th>
<th>Grade</th>
<th>Upper shelf energy (J)</th>
<th>40J transition temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X100</td>
<td>~100</td>
<td>~30</td>
</tr>
<tr>
<td>2</td>
<td>X80</td>
<td>~210</td>
<td>&lt;65</td>
</tr>
<tr>
<td>3</td>
<td>X80</td>
<td>~140</td>
<td>~50</td>
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<td>X80</td>
<td>~220</td>
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<td>~25</td>
<td>~20</td>
</tr>
<tr>
<td>10</td>
<td>X80</td>
<td>~250</td>
<td>&lt;65</td>
</tr>
</tbody>
</table>

*Sub-size specimen (6.7 mm thickness) as the wall thickness is 9.5 mm and transition temperature is the 50% FATT.

The curved DWTT specimens extracted from pipe were ‘straightened’ to ensure that the load point and support points were in the same plane to obtain fracture along the pipe axis. A modified procedure, following the guidelines in BS 7448: Part II: 1997\(^4\), was used with the objective of avoiding any plastic deformation along the intended fracture plane. The specimens from X52 steel tested at 65°C displayed brittle crack initiation (arrow) below the pressed notch in a 100% shear fracture (Figure 1a). However, for the case of X70 and X80 steels, the 100% shear fractures had no evidence that the pressed notch served its original objective of producing cleavage initiation. In the case of X100, the fracture propagated with partial cleavage in planes inclined at approximately 45° to the mode I plane (arrow in Figure 1b). Most fractures classified as 100% shear, except in steels 5 and 9, displayed some degree of splits in planes parallel to the specimen surface.

**Figure 1:** Fracture surfaces of DWTT specimens; (a) steel 9 at 65°C, steels 1(b) at 18°C.

**OBSERVATIONS FROM MODIFIED DWTT SPECIMENS**

The modified DWTT specimens included the back slotted type (see Figure 2) and statically pre-cracked type specimens.

**Figure 2:** Back slotted DWTT specimen

The back slot approach can be considered as a variation of the test procedure adopted by Priest and Holmes\(^5\) who changed the ligament length of the specimen by machining notches to various depths in the DWTT specimen. In their method, the different notch depths meant that energy associated with crack initiation, i.e., the components of energy used up in damage at the notch, specimen deformation and load point indentation would be different.
with different ligament lengths. The alternative method used in the current work aims to vary the ligament length without changing the above mechanics. In attempting to do this, the DWTT specimen design included a standard pressed notch and a slot machined from the back face into which a shim, flush with the surface, as illustrated in Figure 2. The slot and the shimmed face are under compression, and the deformation of the reduced ligament during the bending of the specimen in the fracture process is expected to be the same. Thus, the energy component in producing prior damage before propagation should be identical for the different slot depths (ligament lengths).

A second set of specimens was tested after static pre-cracking. The statically pre-cracked DWTT specimen has been adopted by Wilkowski and Mihelcic and was shown to substantially reduce the total energy absorbed in a standard press notched DWTT specimen by drastically reducing the initiation component.

### Effect of Static Pre-Cracking

In order to display the real effect of static pre-cracking, the load-displacement plot for a PC specimen from steel 2 is superimposed on a corresponding curve for a standard specimen (Figure 3). The curve for the PC specimen has been moved with respect to that of the standard specimen so that the tail ends of the curves approximately overlap each other. Essentially, the display shows how pre-cracking removes the plastic energy (difference in areas under curves) consumed by the standard specimen up to the maximum load. The intention of the static pre-cracking procedure is to reduce the energy consumed for crack initiation and other damage mechanisms that take place in the specimen before commencement of crack propagation. This goal appears to be achieved to a significant extent as crack propagation is usually identified with the portion of the curve beyond the maximum load.

This effect is illustrated in Figure 4 for 100% shear fractures, where the PC total energy levels off with increasing value of standard energy.

![Figure 4: DWTT Energy (Average), 100% Shear Fractures, Each Point is Marked to Identify the Steel](image_url)

**Figure 4:** DWTT Energy (Average), 100% Shear Fractures, Each Point is Marked to Identify the Steel

### Effect of Back-Slotting

Figure 5 presents a set of load-displacement curves for specimens tested from steel 2 with back slot depths of 8, 16 and 24 mm. They are superimposed on the basic curve, and plotted so that all of them have a common origin, to show that for this steel the initial portion of the curve is not significantly affected by this modification. At the tail end, as the propagating fracture encounters the back slot, the load drops suddenly, especially for specimens with back slots of 16 and 24 mm.

![Figure 5: Load-Displacement Plot for Specimens from Steel 2 to Display the Effect of Back Slotting](image_url)

**Figure 5:** Load-Displacement Plot for Specimens from Steel 2 to Display the Effect of Back Slotting

Figure 6 shows fracture surfaces indicating that back slotting did not cause deviation of the fracture path from the intended plane, thus making this an effective approach to...
change the ligament length without changing the interaction mechanics of crack propagation.

Figure 6: Fractures from Steel 2 with Three Back-Slot (Arrow) Depths Compared to the Standard Specimen

Many of the steels evaluated in the program confirmed that back slotting produced curtailment of the load-displacement trace as the propagating fracture interacted with the back slot without significantly affecting the remainder of the load-displacement curve. In two of the steels, 4 and 6, the initial part of the load-displacement curves appear to be affected by the back slot(6). For Steel 9, the curtailment is not clearly defined as a result of the small wall thickness (9.5 mm) and twisting of the specimen.

The increase in energy, determined from the area under the load-displacement curve, as the fracture ligament is increased, should give a good measure of the propagation energy with minimum influence from the energy required for initiating the crack. Thus, a graph of energy absorbed against the ligament length displays the characteristics of energy variation with crack extension. Figure 7 shows this variation for steel 2, and the results show a linear fit is the most suitable, indicating that energy absorbed/unit crack length extension can be determined using this experimental approach. Thus, the slope represents the propagation energy/unit length and the intercept may be considered to account for the energy associated with initiation and plastic deformation remote from the fracture.

Observations from Back Slotted Charpy Specimens

Similar to the DWTT specimens, the load drops suddenly (Figure 8) as the propagating fracture encounters the back slot. The 4 mm deep back slot in the Charpy specimens is proportionally deeper than the 24 mm back slot for the DWTT specimens, i.e., 50% of the ligament compared to approximately 34% in DWTT specimens, therefore, the load drops off much earlier for the 4 mm back slot in the Charpy tests. As for the DWTT specimens, a plot of energy absorbed vs. the fracture ligament length displays the characteristics of energy variation with crack extension, and the slope could be interpreted to represent the propagation energy/unit crack length extension.

DISCUSSION

In the case of the DWTT specimens, from steels that did not result in anomalies as indicated in the previous section, a linear relation was obtained for the absorbed energy vs. fracture ligament length (Figure 7). The characteristic slope of the relation, for each steel, can be considered a representation of the normalized propagation energy as described in that section. The first term of the expression developed by Priest and Holmes(3) is the specific energy component related to the fracture process while the second is the contribution from remote plasticity and initiation. The slope divided by the specimen thickness in the current work, therefore, corresponds to the specific
energy term in the work of Priest and Holmes. From this comparison, it could also be also inferred that the energy associated with remote plasticity and initiation of the crack are not included in the propagation energy derived from slope.

The total propagation energy for a standard DWTT specimen can be obtained by multiplying the slope \((J \text{ mm}^{-1})\) by the ligament length \((71.12 \text{ mm})\). Figure 9 shows specific propagation energy as the ordinate vs. the specific total energy for standard PN DWTT specimens as the abscissa. (In this figure, the primary axes are given in imperial units for the convenience of comparison with work of others\(^5\).) The specific energy is obtained by normalizing the energy with the projected area of the fracture in the 2D mode I fracture plane. Propagation energy derived from both back slotted and PC specimens are shown. The data points are from current work, with the associated steel # I.D. marked. Results for some steels are not displayed due to the anomalies. The relationships, equations 1a and 1b, the latter being the more conservative one, are from the work of Wilkowski and Mihell\(^5\).

\[
(E/A)_{BN-DWTT} = 0.0309(E/A)_{PN-DWTT}^{1.2} - 0.098(E/A)_{PC-TDT} - 1500 \quad (1a)
\]

\[
(E/A)_{BN-DWTT} = 175((E/A)_{PN-DWTT})^{0.385} - 1500 \quad (1b)
\]

where, 
\((E/A)_{BN-DWTT} (\text{ft-lb in}^{-2}) = \text{Total impact energy (E) of a brittle-notched (BN) DWTT specimen divided by the cross-section fracture surface area (A) of the specimen, and}
\]
\((E/A)_{PN-DWTT} (\text{ft-lb in}^{-2}) = \text{Total impact energy (E) of a standard PN DWTT specimen divided by the cross-section fracture surface area (A) of the specimen.}

The specific propagation energy derived from the back sloting is lower than the specific total energy as can be easily observed by visualizing a 1:1 linear slope in Fig. 9. Further, the specific propagation energy, from the back slotted method, for most steels are lower than that predicted by equation 1b. On the other hand, the propagation energy from PC specimens fit the relationship 1b, developed by Wilkowski and Mihell\(^5\). This shows that the back sloting approach is effective in removing initiation energy that is still left in the PC specimens.

Following the approach used for the DWTT specimens, total propagation energy for standard Charpy specimens can be also obtained by using the slope of the absorbed energy vs. ligament length relation. Figure 10 shows specific propagation energy vs. the specific total energy from standard Charpy specimens (abscissa).

In contrast to the results obtained for propagation energy from the DWTT specimens that show the leveling off effect as the total energy (abscissa) increase (Figure 9), the Charpy results are generally lower than the 1:1 slope line. Because the process zone for initiation is a much larger fraction of the total ligament in the Charpy test (particularly for high toughness steels), the calculation of total propagation energy from the slope is subject to much greater errors. For this reason, propagation energy estimated directly from back-slotted Charpy tests may be less useful.

The best measures of propagation energy were obtained from the two sets of results shown in Figure 9. The results represented by the filled diamonds are unique to this work, while the those represented by the open triangles are derived from the PC method that has been developed by others\(^5\). The propagation energy from the back slot method was compared with; (a) true fracture strain \((\epsilon_f)\), (b) uniform elongation \((\epsilon_u)\) and (c) area under the true stress \((\sigma_T)\)-true-strain \((\epsilon_T)\) curve (A). None of the three tensile properties showed strong correlation with the propagation energy. This
is similar to the findings of Priest and Holmes, who found little correlation between fracture energy and the various energy and extension values from the tensile tests.

The current methodologies for predicting ductile fracture arrest in pipelines, such as the Battelle two-curve approach, make use of Charpy energy. For conventionally processed steels, a linear relationship has been used to convert total DWTT energy to Charpy energy. Methods of directly using energy from DWTT specimens in similar models have been proposed. In the method outlined below, a correlation between Charpy and DWTT energy allows the conversion of DWTT propagation energy into an equivalent Charpy propagation energy.

Figure 11 presents the specific energy relation from standard PN DWTT and Charpy specimens for the steels used in this program. (As in Figure 9, the primary units are Imperial for the same reason.) The data points represent 100% shear fractures albeit with splits. The standard linear relation for older pipeline steels is also displayed for comparison and this works well for specific Charpy energies up to 1.27 J mm\(^{-2}\) (600 ft-lb in\(^{-2}\)). For the steels in the current investigation a non-linear fit is better. The comparison of DWTT and Charpy energy was from tests at the same temperature.

In order to estimate an effective specific propagation energy from the absorbed energy in the Charpy test, the former may be derived from the specific propagation energy from the back-slotted results in Figure 9. The non-linear relationship between the specific absorbed energies in the standard DWTT and Charpy can be used for this purpose. The results of this process are presented in Figure 12. This method of determining the equivalent Charpy propagation energy is in principle the same as that adopted by Wilkowski and Mihell. If burst test results were available for any of these steels, this equivalent Charpy propagation energy could be compared with the predicted Charpy energy in the Battelle two-curve approach.

**CONCLUSIONS**

The focus of the experimental program was in determining a 'propagation energy' from specimens with back-slots. The modification was made to standard specimens that are currently used to measure toughness of pipeline steel. The back-slot modification, in principle, provided a curtailment of the load-displacement curve as the propagating crack interacted with the back slot. This was the case for both DWTT and Charpy specimens. The linear relationship between absorbed energy and ligament of the back slotted DWTT specimens corresponds to the fracture propagation energy term derived by Priest and Holmes. This comparison further supports that the back slotted method is successful in allowing the other components of energy expended in the DWTT specimen to be eliminated.

The total energy from the PC DWTT specimens was about 2/3rds of the energy from the standard PN specimens, whereas propagation energy obtained from the back slotted PN specimens was less than the energy obtained from PC DWTT specimens. Energy determined by the back slotted procedure, in the Charpy specimens, did not show a decreasing slope with increased total energy as was the case for the DWTT specimens. Instead, a roughly linear relationship was observed. Parameters derived from tensile tests showed a weak correlation with propagation energy.

The back-slotted DWTT represents a promising new technique for the determination of fracture propagation resistance of pipeline steels. Further work will be needed to assess the accuracy of the procedure and to develop a recommended test protocol. The incorporation of such testing into future full-scale test programs would provide a valuable opportunity for validation.
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REFERENCES

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