THE INFLUENCE OF TEST CONDITIONS ON THE FRACTURE RESISTANCE OF LINEPIPE STEELS

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ABSTRACT

The energy for fully shear fracture has been measured for a variety of materials using different types of test piece. Equations have been derived relating the energy per unit area for fracture to the ligament length, (W-a), of the test piece, both at ambient temperature and also at lower temperatures. This relationship was found to be the same for CT or SENB tests and was unaffected by either thickness or ligament length above a ligament length of about 25 mm; at smaller values, however, there was an effect of thickness which was related to the toughness of the material. Temperature did not appear to have a significant effect within the range examined. Tension tests gave similar S_c values, but R_c increased by a factor of two. Results of impact tests were found to fit the same expression as slow rate tests, but with higher R_c and S_c values. The effect of strain rate, however, appeared to be non-logarithmic. The difference between notched and fatigue cracked test pieces was found to be a function of R_c and therefore independent of ligament length.

KEYWORDS

Fracture properties; fracture mechanics; fracture tests; fracture toughness; fracture; pipeline gas; strain rate; Charpy tests; impact tests.

INTRODUCTION

Recent work (Holmes and co-workers, 1977) has confirmed that the shear fracture propagation energy of steels is governed by two parameters. The first parameter, R_c, is the energy required to create a given area of fracture surface and the second parameter, S_c, is the energy required to deform a given volume of material in close proximity to the crack. Before a practical testing procedure can be developed, however, information is required on a number of factors which may influence the linearity of the derived relationship

$$U/B(W-a) = U/A = R_c + S_c(W-a) \quad (1)$$

where B is thickness, W is width and a is crack length. These factors are thickness B, ligament length (W-a), test piece geometry (i.e. compact tension, bend and pure tension tests), notch acuity, strain rate and temperature. The above information should enable an estimate of the R_c and S_c values to be calculated unambiguously and used to quantify the resistance to fracture of pipelines more precisely than hitherto. It should be emphasised that the investigation has been confined to materials exhibiting fully shear fracture behaviour; the presence of significant amounts of cleavage or plane strain fracture would produce a pronounced thickness effect for instance and would not be acceptable in the quality requirements for this type of steel.

MATERIAL FOR INVESTIGATION AND EXPERIMENTAL DETAILS

The material for this investigation consisted of samples of pipeline material from six steels, cast Nos. 1 to 6, supplied by BSC Tubes Division, in the controlled rolled (CR) normalised (N) or quenched and tempered (QT) condition. The chemical analysis results for the six steels are shown in Table 1. Transverse tensile properties are presented in Table 2 together with the corresponding 2/3 Charpy impact values.

Test pieces of the compact tension (CT) type (W = 50, 100 or 200 mm), were machined from each material so that the fracture plane was parallel to the rolling direction, prior to fatigue pre-cracking and testing under displacement control. For all the large size test pieces (W = 200 mm) anti-buckling clamps were used. Load and ram displacement were recorded and this enabled measurements to be made of the total energy absorbed. Where necessary the reduced thickness test pieces were machined from both the centre and surface regions of the plate in order to minimise any effect due to through thickness variability.

A series of transverse single edge notched bend (SENB) type test pieces having an overall span to test piece width ratio of 4:1, were tested the same way as the CT tests. A similar series of SENB test pieces were tested in impact at 20°C on the dynamic tear testing machine at British Gas Corporation, Newcastle. The overall span to test piece width ratio of 3.3:1 was the same as that generally used in the Battelle test. Charpy type test pieces were tested at 20°C on a Charpy impact machine.

Transverse tension type test pieces, double edge notched (DENT) or centre notched (CNT), were fatigue cracked to a ligament length of approximately 50 mm and then tested at 20°C.

EXPERIMENTAL RESULTS

Slow Rate CT Tests

Test results for the CT test pieces at 20°C, in terms of the energy absorbed per unit area of fracture, are shown as a function of the ligament length for a selection of the materials in Fig. 1, where it can be seen there were linear relationships of the form shown in

TABLE 1 Chemical Analysis

Cast No.	Analysis, wt %										
	C	Mn	Si	S	P	Al	N	Nb	V	Ce	Ce/S
1	0.11	1.37	0.30	0.017	0.007	0.014	0.0067	0.033	-	0.014	0.8
2	0.12	1.44	0.31	0.011	0.008	0.054	0.0071	0.034	-	0.015	1.4
3	0.09	1.36	0.32	0.015	0.011	0.024	0.0055	0.033	-	0.027	1.8
4	0.13	1.18	0.31	0.009	0.012	0.014	0.0054	0.032	-	0.021	2.3
5	0.12	1.61	0.37	0.010	0.014	0.024	0.011	0.040	0.005	-	-
6	0.11	1.48	0.29	0.006	0.018	0.022	0.013	0.050	0.070	-	-

TABLE 2 Mechanical Properties and Material Constants

Cast No, Plate No. and Condition		B mm	YS N/mm^2	UTS N/mm^2	2/3C_v @ 20°C J	Slow Rate R_c J/mm^2	Slow Rate S_c J/mm^3	Impact Rate R_c J/mm^2	Impact Rate S_c J/mm^3
1	CR	12.7	427	524	51	0.53	0.018	0.73	0.034
2	CR	12.7	460	564	68	0.94	0.022	1.20	0.039
3	CR	12.7	420	502	84	1.09	0.027	1.48	0.048
4	N	12.7	405	539	98	1.30	0.027	2.22	0.037
	QT	12.7	655	728	45	1.07	0.018	-	-
5 /1	CR	12.7	572	636	26	0.36	0.011	0.38	0.019
/2	CR	12.7	538	624	29	0.45	0.011	0.34	0.026
6 /1	CR	12.7	558	643	44	0.51	0.016	0.69	0.026
/2	CR	12.7	534	608	59	0.75	0.017	0.93	0.033
/3	CR	16.0	491	596	59	0.70	0.017	0.98	0.034
/4	CR	35.0	-	-	-	-	-	-	-

Equation (1); the statistically derived constants are presented in Table 2. There was, however, a deviation from linearity for ligament lengths smaller than approximately 25 mm and this can be seen for cast No. 2 in Fig. 2. Controlled rolled, normalised and also quenched and tempered materials assumed the same general relationship. For the quenched and tempered material, however, the R_c and S_c values were significantly lower than for the original normalised material, which was probably related to the higher tensile properties of this material. Similar data were obtained at various test temperatures in the range 0 to -50°C for the cerium treated materials and an example for cast No. 2 is shown in Fig. 2 where it can be seen that there was very little effect of temperature on the energy per unit area values.

No significant difference was observed in the results for test pieces machined from the surface or centre region of the material but nevertheless the average values were used. It can be seen that there was generally very little effect of thickness on the energy per unit area values for ligament lengths greater than 25 mm, Fig. 3.

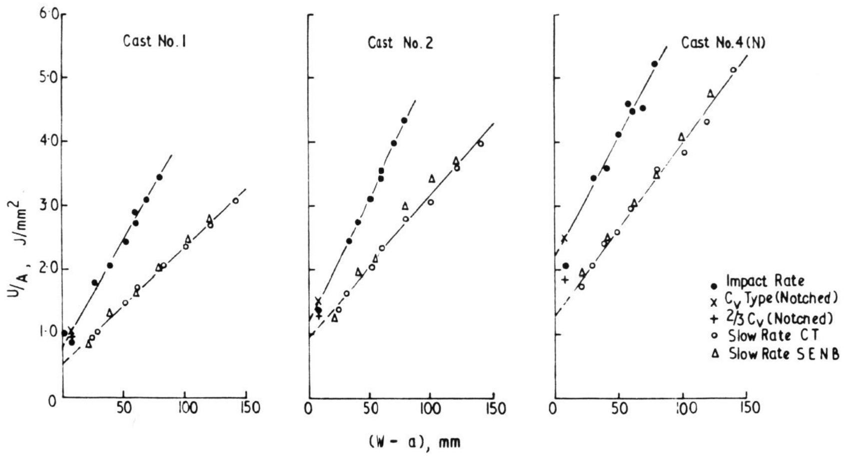

Fig.1 Energy per unit area as a function of ligament length

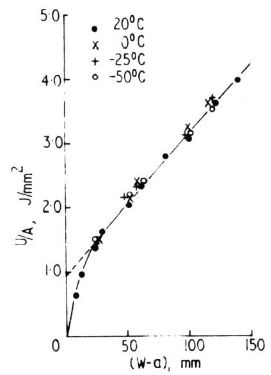

Fig.2 Influence of temperature and ligament size

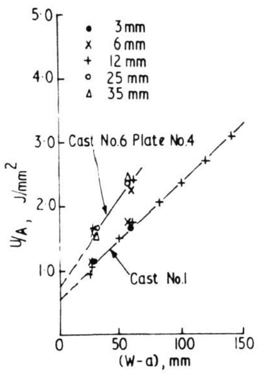

Fig.3 Influence of thickness

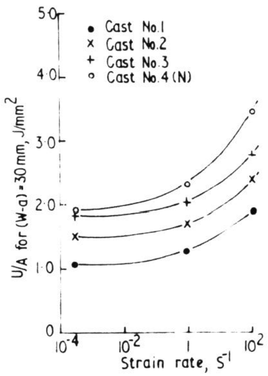

Fig.4 Influence of strain rate

Varying Rate CT Tests

Energy values were obtained from tests carried out on the cerium treated materials at various temperatures and at two displacement rates. There was an increase in the energy value from slow to fast rate test and this was largely independent of the testing temperature in the range 20 to -50^{o}C. The average values are shown in Fig. 4 for strain rates of approximately 0.0003 and 0.9/s which were obtained from the following equation due to Irwin (1964),

$$\dot{\epsilon} = 2\sigma_y/Et \qquad (2)$$

where σ_y is the yield stress at the requisite strain rate, t is the time to the deviation from linearity, E is Young's Modulus.

Slow Rate SENB Tests

U/A values for the SENB type test pieces at 20^{o}C, are shown as a function of the ligament length for three of the cerium treated materials in Fig. 1, where it can be seen there were almost identical linear relationships to those observed for CT type test pieces.

Impact SENB Tests

U/A values for the impact SENB type test pieces together with those for the Charpy type test pieces at 20^{o}C, are shown as a function of the ligament length for the same four materials selected for the slow rate CT tests in Fig. 1. Again it can be seen there were linear relationships similar to those observed for CT tests and results from plate thickness notched Charpy type test pieces appeared to fit these relationships, Table 2. The difference between the energy values for a notch as against a fatigue crack in plate thickness Charpy type test pieces, $(\Delta U/A)_1$ is shown in Fig. 5 as a function of the 2/3 Charpy value at 20^{o}C where it can be seen there was an increase in the difference with increasing toughness of the material. For the notched Charpy type test pieces, the difference between the energy values for plate thickness as against 2/3 thickness, $(\Delta U/A)_2$, is shown as a function of the 2/3 Charpy value in Fig. 6. Here there appeared to be very little effect for toughness values up to approximately 50J; however, at higher toughness levels the effect of thickness became increasingly more pronounced. Results from the cerium treated materials are included in Fig. 4 at a strain rate of 100/s, which is approximately two orders of magnitude greater than the maximum obtained on the electro-hydraulic machine.

Slow Rate Tension Tests

U/A values from the DENT and CNT type tests, are shown as a function of the ligament length for Cast No. 2 in Fig. 7. The results for the two larger ligament sizes were obtained from tests carried out at TNO, The Netherlands in a collaborative programme. For the four tests the statistically derived equation relating the fracture energy to the ligament length was as follows:

$$U/A = 2.05 + 0.024(W-a) \qquad (3)$$

This is a similar expression to that observed by Cotterell and Reddel (1977) for this type of test piece.

DISCUSSION OF RESULTS

Influence of Thickness and Ligament Length

Conflicting information has been available on the influence of thickness on the shear fracture resistance of linepipe materials. Indeed several authors make different specific allowance for this in calculations for predicting the performance of pipelines using a power

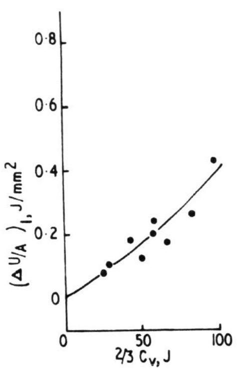

Fig.5 Influence of notch acuity on Charpy type values

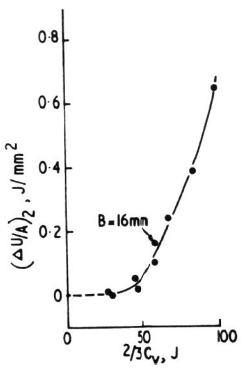

Fig.6 Influence of thickness on Charpy type values

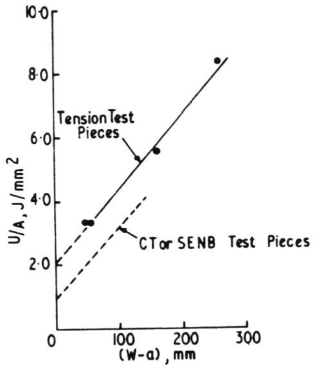

Fig.7 Energy per unit area as a function of ligament length

term for B in the range 0.25 to 1; for example, Judy and Goode (1973) use a power term factor of 0.5. The explanation for these different opinions becomes apparent when a comparison is made of U/A values for test pieces of different thickness at different ligament length. When for instance (W-a) values are greater than 25 mm as in Fig. 3 there is no influence of thickness on U/A values, but when the ligament size is reduced to below about 20 mm then a singificant difference is observed. The difference is particularly marked in Charpy size test pieces which of course has been the standard test method for many years. The magnitude of the difference is clearly shown to be a function of the toughness of the material tested in Fig. 6, where a comparison is made between U/A values for full thickness (B = 12.7 or 16.0 mm) and 2/3 (B = 6.67 mm) nominal Charpy tests at different levels of toughness.

From Fig. 2 it is shown that below a ligament size of about 25 mm the data do not fit the linear relationship; a reduction in U/A occurs so that the values extrapolate to a value of zero at zero ligament length. The minimum ligament length necessary to avoid such deviations is related to the thickness and toughness of the steel so that this size probably decreases with increasing thickness but increases with increasing toughness. Consequently Charpy type test pieces exhibit a greater influence of thickness for the tougher materials. Providing a minimum ligament size of about 25 mm is used then data from all materials should fit the linear relationship. However it has already been pointed out that the difference between U/A values for machined notched and fatigue cracked test pieces is a function of 2/3 C_V. The values of U/A for the notched full thickness Charpy type test pieces are therefore increased in proportion to their toughness so that they fit the linear relationship from pre-cracked large ligament impact test pieces almost exactly (Fig. 1). This coincidence may be of use in avoiding the necessity for at least one large sized impact test and has the advantage that the greater the difference in ligament length the more accurately can both R_c and S_c be determined.

Influence of Temperature

U/A values plotted as a function of ligament length in Fig. 2 are found to decrease only slightly with increasing temperature in the ambient temperature range of interest. The constants R_c and S_c are therefore both also relatively independent of temperature in this region.

Influence of Rate

The relationship illustrated in Fig. 4 shows that on increasing the displacement velocity from that of a conventional fracture toughness test (strain rate = 0.0003/s) to that of an impact test, (strain rate = 100/s), the total fracture energy is increased by approximately 40% for a range of materials. The difference in rate between these two tests is 10^6 and an intermediate test 10^4 times faster than the slowest rate indicates that the fracture energy does not fit a convenient logarithmic relationship as might be expected.

The relationship between slow and impact rate R_c and S_c values are illustrated in Fig. 8. The increase in R_c was far more pronounced at high R_c values whereas at low levels it appeared to be insignificant. In contrast the S_c values for these materials always increased with rate and the average factor was about 1.8. Now if small scale test results were used to assess the influence of rate then, because U/A values for these are closely related to R_c, errors could be made in evaluating the rate sensitivity of low toughness materials. In fact, as illustrated in Fig. 8, strain rate behaviour is dominated by S_c, and therefore the overall fracture resistance of larger structures will always increase with rate.

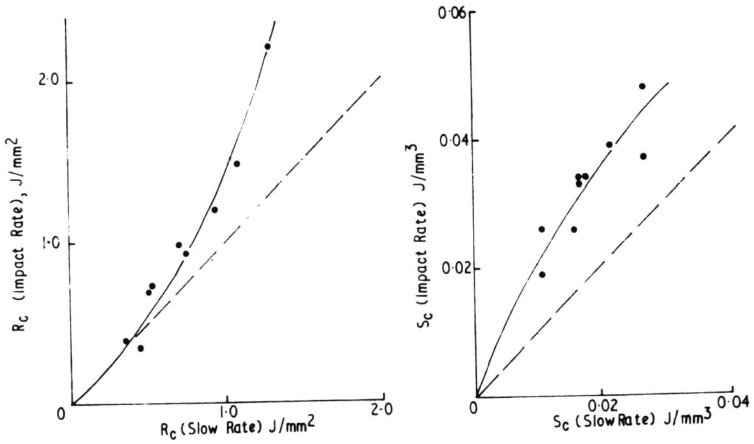

Fig.8 Relationships between fracture constants for impact and slow rate tests.

Influence of Notch Acuity

The data shown in Fig. 5 indicate that $(\Delta U/A)_1$ increases with increasing 2/3 C_v; a linear relationship with R_c was also established. Furthermore, values of $(\Delta U/A)_1$ for test pieces with ligament lengths varying between 4 and 80 mm of cast No. 2 are also virtually constant. This means that for any given material the difference between cracks of different acuity is reflected in a change of R_c but not S_c. Since $(\Delta U/A)_1$ varies linearly with R_c it follows that R_c calculated from fatigue cracked test pieces is a constant proportion of R_c calculated from machined notched test pieces. The data obtained indicated that the ratio between the two was about 0.85. At the large ligament lengths likely to be related to the fracture of pipeline the fracture propagation energy is dominated by plastic deformation governed by S_c and any errors introduced by this approximation of R_c will be small.

Influence of Test Piece Geometry

Comparison of the U/A values for tension test pieces (either DENT or CNT) and for CT or SENB test pieces in Fig. 7 indicates that the R_c value for the former test pieces is approximately double that of the latter whilst the S_c value is the same. A similar comparison has been performed on casts Nos. 1, 2 and 4 and the R_c values for tension tests were increased over those for CT or SENB tests by factors of 2.1, 2.0 and 2.0 respectively. This therefore indicates that the approximate factor of two for R_c and the constant value for S_c are independent of the material tested.

The difference in R_c values is probably associated with the compressive strain towards the back face of both CT and SENB type test pieces which is not present in the tension test.

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