DYNAMIC FRACTURE TESTING OF POLYETHYLENE

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Dynamic fracture tests on three point bend specimens of an HDPE were carried out using a instrumented drop-weight tester. To reduce the oscillations in the load signal a damping material was placed on the specimens. For the determination of G_c both total fracture energy and fracture energy till maximum load were used. K_c was determined from the maximum load. The effects of both side grooving and testing velocity on load signal, fracture toughness and fracture surface topology were investigated. A relation was found between velocity and craze zone, predicting the velocity to achieve complete brittle failure. With a SEM the fracture surfaces were studied and a new fracture model is proposed.

INTRODUCTION

Normally polyethylene behaves as a ductile polymer but when subjected to high strain rates it can fail brittle. Especially in welded polyethylene pipe applications for water and gas distribution the consequences of unstable failure are serious and a high toughness is essential. For future grade development a good measurement of the fracture toughness and understanding of the phenomena leading to brittle failure are necessary.

In the past only the energy loss of the striker to fracture a charpy specimen was measured to characterise the fracture toughness. Now there are several instrumented systems which give load-time information from the impact event and a range of options exists for both data capture and analysis. From the load-time trace it is possible to determine the load and fracture energy at the moment of fracture initiation which leads to the fracture toughness parameters K_c and G_c as stated in the draft protocol of the ESIS TC4 (1).

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In impact testing the load-time signal has a superimposed oscillation due to dynamic effects arising from the acceleration of the specimen. These dynamic effects have been studied by other workers (2,3) leading to the conclusion that when the oscillations are relatively high, the errors in the determined fracture toughness become high.
The present work has studied the possibilities to reduce the oscillations and the influence of both side grooving and testing speed on the dynamic fracture toughness of a high density polyethylene. For a better understanding of the dynamic fracture process the fracture surfaces are studied.

THEORY

Using linear elastic fracture mechanics (LEFM) the toughness can be characterised in terms of the critical stress intensity factor, K_C, and the critical energy release rate, G_C, at fracture initiation. To ensure that a minimum value of toughness is obtained the crack must be sufficiently sharp. Also a state of plane strain at the crack tip is required so that thickness normal to the crack front must be sufficient.
In the ASTM metals standard E399 the standard procedure for K_C measurement is given. For single edged notched bend specimens K_C can be calculated using:

$$K_c = \frac{P_{max} S}{B W^{\frac{3}{2}}} f\left(\tfrac{a}{W}\right) \qquad (1)$$

with the requirements:

$$0.45 < a/W < 0.55 \text{ and } a, B, (W-a) \geq 2.5\left(\frac{K_c}{\sigma_y}\right)^2 \qquad (2)$$

G_C can be determined via the multiple specimen route as advocated by Plati and Williams (4). For this a series of bars with different notch lengths are fractured and the fracture energy is measured. G_C can then be calculated from a straight line graph according to the equation:

$$U = G_C BW\phi \qquad (3)$$

where ϕ is a known function of crack length (1, 4).
For very brittle polymers the total fracture energy can be used for G_C calculation because all the energy is involved in initiating unstable fracture. In tough polymers there is an extra energy consumption after initiation so U must be calculated from integrating the load-displacement curve till peak load (assuming that the crack does not initiate before peak load). The G_C from total energy and from energy till peak are denoted $G_C{}^T$ and $G_C{}^P$ respectively.

In the ESIS protocol (1) the following restrictions regarding the oscillations are made: The first oscillation peak must be lower than 50% of the maximum load. When the load rises above 50% of the maximum the amplitude of the oscillation must be lower than 5% of the maximum load. The time to fracture must be more than three times the period time of one oscillation. The models of Williams (5) describing the oscillations indicates that the oscillations can be reduced by decreasing the contact stiffness or by increasing the stiffness of the specimen.

EXPERIMENTAL

Specimen preparation

The specimens (BxWxS = 10x20x80mm) are taken out of 19 mm thick extruded HDPE plates. The direction of the specimens was chosen so that the crack growth direction was perpendicular to the extrusion direction and the fracture plane was perpendicular to the plate surface. For one G_c determination 16 specimens with a/W varying from 0.2 to 0.7 were used. The specimens were notched by pressing a fresh razor blade with a speed of 50μm/min into the milled notch. The razor notch depth was at least 1.5 mm. The side grooves give a thickness reduction of 20% and have a root radius of 0.4 mm.

Instrumental impact system

All impact testing was performed using a instrumented drop-weight tester. The mass of the drop weight was 70.3 kg and the maximum drop height was about 2m. A tup according to ASTM D-256 with semiconductor strain gages was mounted on the drop-weight and the load signal was recorded with a digital oscilloscope. A slotted "flag" attached on the falling weight, passing through a photo diode, just before the impact, was used to trigger the data capturing and to measure the impact speed. A PC was used to process and store all captured data and to transform the stored load-time trace into a load-displacement curve. Both total fracture energy and energy till maximum were calculated by integration.

Load oscillations

To reduce the oscillations in the load signal the contact stiffness was decreased by placing a rubber pad on the specimen at the place were it is hit by the striker. For testing speeds of 1 m/s 0.5 mm thick rubber and for higher speeds 1.2 mm thick rubber was used. To increase the specimens stiffness the specimen size was taken as small as possible, but still large enough to obtain (probably) valid K_c values.

RESULTS

In the next table an abstract of the results is given.

Table 1 Overview of the results from the impact tests on a HDPE.

v	side-groove	Damping	Oscill.: protocol requirements			Craze	K_c	G_c^T	G_c^P
m/s		mm Rub.	1^{st}>50%	$t_f>3\tau$	5%	mm	MPa√m	kJ/m²	kJ/m²
1	-	-	a/W>0.5	+	-	2.4	3.0±0.3	20.5±1.1	8.8±0.8
1	-	0.5	a/W>0.63	+	+	2.5	2.8±0.2	23.2±2.4	8.8±0.4
1	+	0.5	a/W>0.6	+	+	2.3	3.1±0.2	8.5±0.3	8.6±0.3
1.5	+	1.2	a/W>0.6	+	+	1.9	2.9±0.1	9.8±0.3	8.9±0.3
2	+	1.2	a/W>0.6	-	+	1.6	2.9±0.1	9.7±0.3	8.1±0.2
3	+	1.2	a/W>0.4	-	+	1.2	2.8±0.3	8.7±0.6	7.2±0.9

Effect of damping material

The effect of applying damping material on the load signal is demonstrated in figure 1. At a testing speed of 1 m/s and without damping material the oscillations in all specimens are larger then permitted. With damping material only the load signals of the specimens with a/W>0.6 are invalid. This is because the decrease in stiffness of the specimens due to the deep notch depth. At speeds of 2 m/s and higher the oscillations increase and the time to fracture decreases. No significant change in K_c or G_c was found as a the result of applying the damping material.

Effect of side grooves

Side grooving has a large effect on the load signal. Specimens without side grooves (figure 1a) show after crack initiation (abrupt drop in load signal) a large unloading tail. The fracture surface (figure 2) shows shearlips and crack arrest phenomena leading to an appreciable difference between the total and maximum load fracture energy. By this G_c^T and G_c^P differ considerably (figure 3). Plane specimens show also a clearly curved craze zone that decreases in length towards the specimen surface. By applying side grooves the craze zone shows no variation across the thickness, no shearlips are formed, and crack arrest after maximum load disappears. As a result the unloading tail disappears and the difference between total and maximum load fracture energies become relatively small and hence also the differences in derived G_c values (figure 4).

Velocity effects

Due to the oscillations it was not possible to determine G_c or K_c values above speeds of 3 m/s. Between 1 and 3 m/s G_c drops from 8.6 to 7.2 kJ/m^2 but K_c remains almost constant al a level of 3,0 MPa$\sqrt{m}$. The craze zone width decreases with increasing velocity showing a linear relation with the logarithm of the velocity in the range between 1 and 6 m/s (figure 5).

Fracture surfaces

Figure 6 shows a photographic overview of the region just ahead the notch tip. In this region 3 zones can be distinguished:

1 A small smooth zone of about 0.2 mm. On both macroscopic and microscopic scale the fracture in this region appears to be brittle.

2 A patchwork zone with decreasing coarseness. This zone is associated with craze forming ahead of the crack tip. The patches are formed because the crack propagates through the craze/solid interface and is jumping between the two interfaces. The photograph in figure 7 shows a side view of one patch. The edge of the patch shows large deformations which can be explained as follows: When the crack jumps to the other interface the material in the craze is not separated, as soon as the crack opening becomes larger the material between the patches is torn apart in a ductile way. Figure 8 shows the described mechanism in a schematic way.

3 A hackle structure, produced by the unstable brittle fracture emanating from the craze zone at maximum load. Gradually the hackle structure disappears and changes into a dimple structure associated with decreasing crack growth velocity.

DISCUSSION

By extrapolating the data of tension tests at different testing speeds a yield stress of approximately 35 MPa was found for a speed corresponding to the deformation rate during impact testing. Equation 4 with a K_c of 3.0 MPa$\sqrt{m}$ then results into a minimum thickness for a valid toughness value of 18 mm. Although the specimens tested are 10 mm thick the measured toughness is probably a plane strain value because there is no significant difference between the values obtained from the plane specimens and the side grooved ones.
No clear relation was found between G_c and the craze zone width as observed by Hemingway et al (6). Extrapolating the craze zone width versus testing velocity data to zero craze zone width, i.e. complete brittle fracture initiation, results in a minimum testing velocity of 12 m/s.

CONCLUSION

A rubber pad can be applied to reduce the oscillations and has no effect on the measured toughness values.
When testing specimens with side grooves it doesn't matter whether total or maximum load fracture energy is used for G_c determination. This enables the application of an uninstrumented pendulum to determine G_c.
Although the specimen thickness is smaller then the minimum thickness according ASTM E399 the measured values appear to be plane strain values.
Higher testing velocities lead to lower G_c values and to smaller craze zones. By extrapolation to zero craze width the velocity for complete brittle fracture initiation can be found.

SYMBOLS USED

ϕ = energy calibration factor
σ_y = yield stress (N/mm^2)
τ = period time of one oscillation (s)
a = crack length (mm)
B = thickness of specimen (mm)
G_c = critical energy release rate (kJ/m^2)
K_c = critical stress intensity factor ($MPa\sqrt{m}$)
P = force (N)
S = span (mm)
t_f = time to fracture (s)
u = displacement (mm)
U = energy (J)
v = velocity (m/s)
W = height of specimen (mm)

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(6) Hemingway, A.J., Channell, A.D. and Clutton, E.Q., Plast. Rub. Comp. Proc. Apll., Vol. 17, 1992, pp. 147-155

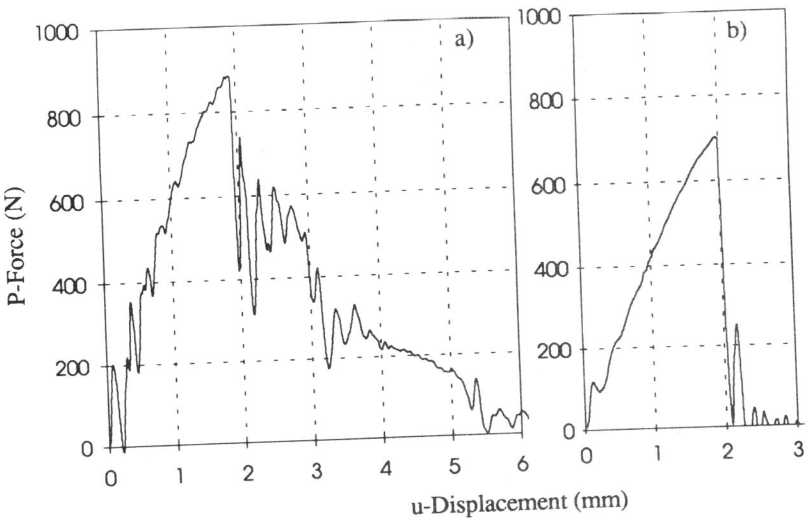

Figure 1 Load signal: a) specimen without sidegrooves without damping
b) specimen with sidegrooves with damping

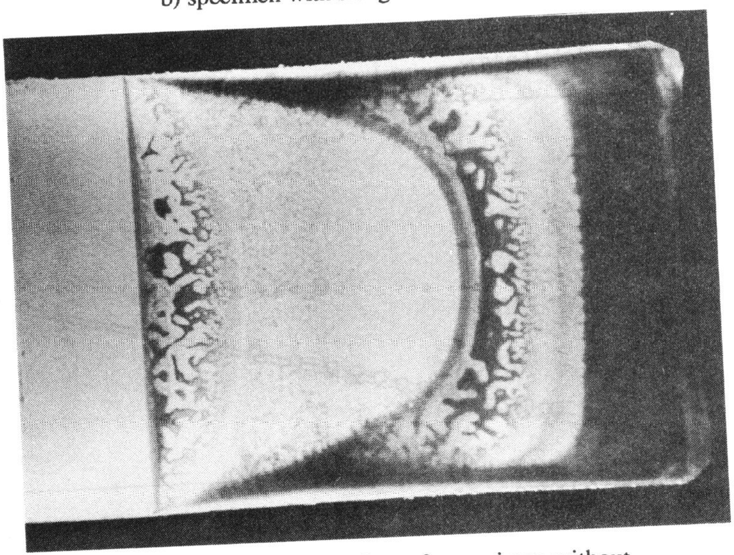

Figure 2 Photograph of the fracture surface of a specimen without sidegrooves (Lightmicroscoop 6.3x)

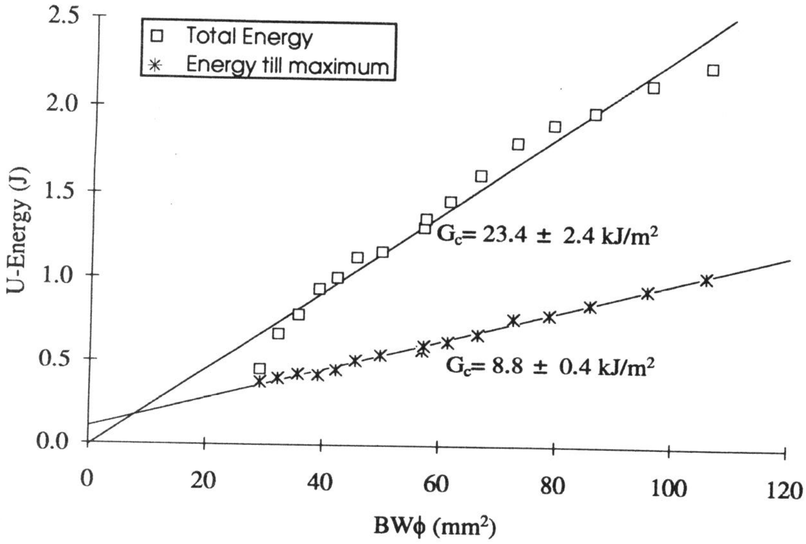

Figure 3 G_c determination for specimens without sidegrooves

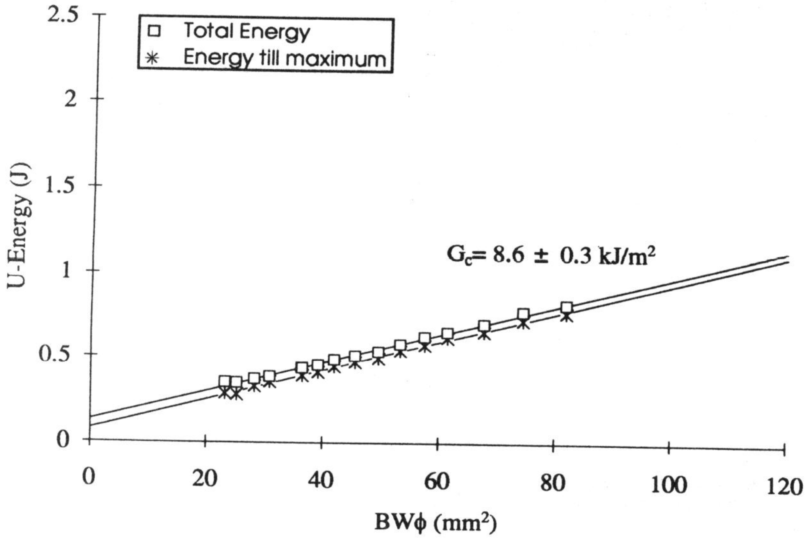

Figure 4 G_c determination for specimens with sidegrooves

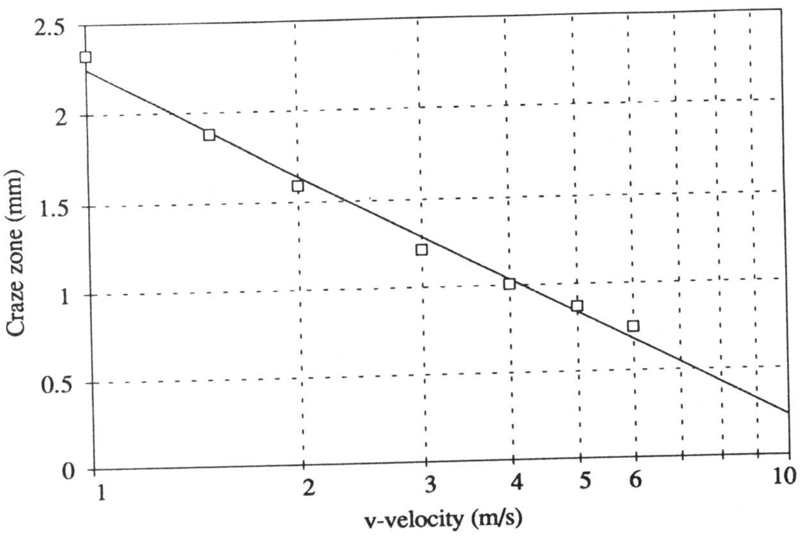

Figure 5 Craze width variation with testing velocity

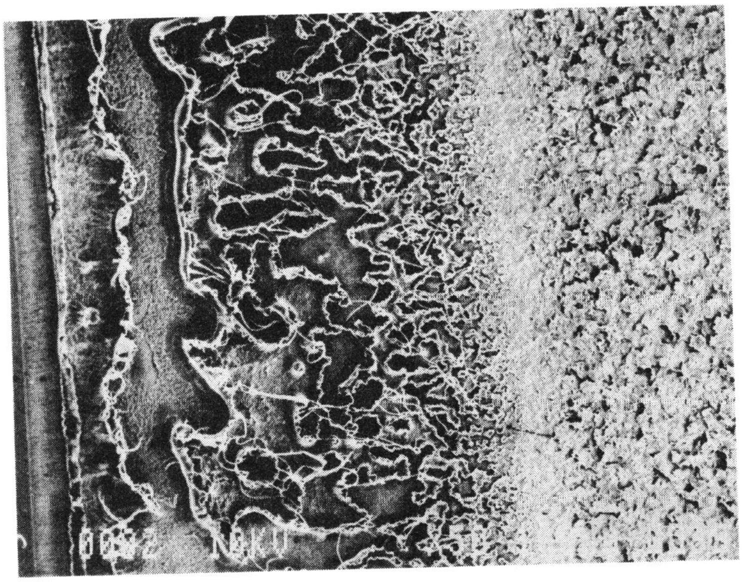

Figure 6 Photograph of the fracture surface (SEM 50x)

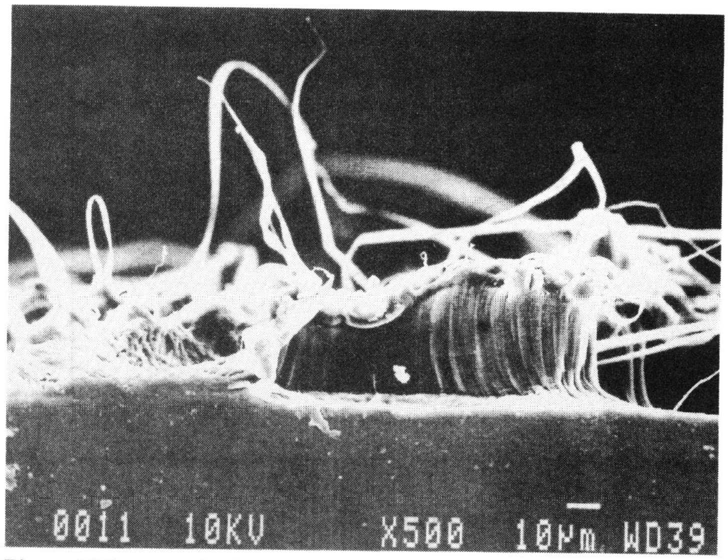

Figure 7 Photograph of the cross section of one patch (SEM 500x)

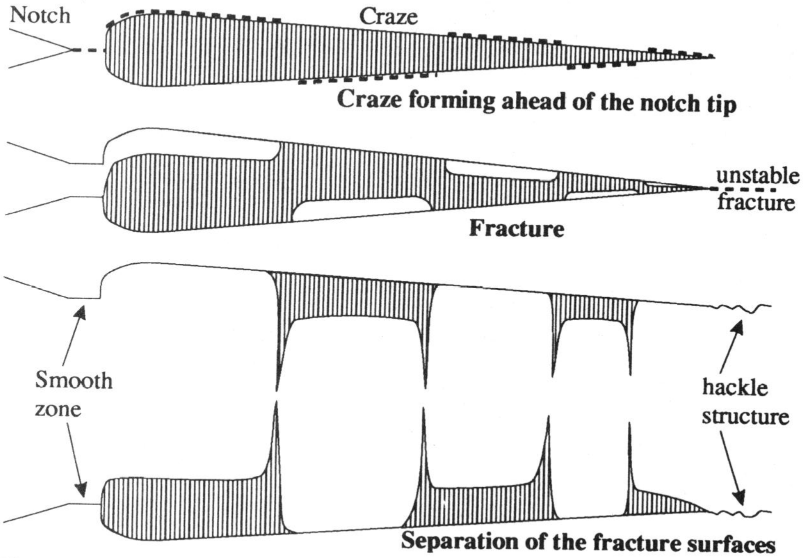

Figure 8 Schematic diagram showing the mechanism of formation of the patchwork structure (▬ ▬ ▬ ▪ = path of crack growth)