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Rapid crack propagation in polyethylene pipe: combined effect of strain rate and temperature on fracture toughness

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The need to predict the mechanical behaviour of polymers is motivated by the increasing use of these materials in structural applications. In order to consider safety in the design of engineering components, the question of a criterion for rapid crack propagation has been investigated in a medium density polyethylene (MDPE) used to extrude pipes for gas distribution. Work on the strain rate–temperature equivalence ($\dot{\varepsilon} \leftrightarrow$ T) was performed to study the yield stress, σ_s, as a function of $\dot{\varepsilon}$ and *T*. A shifting procedure enabled a behavioural master curve, σ_s versus $1/(a_T\dot{\varepsilon})$ to be drawn, where a_T is the shift factor. Both cracked-ring and Charpy specimens were tested to characterize the fracture toughness K_{IC}(T) of the MDPE. The values of the K_{IC}(T) based on linear elastic fracture mechanics are superposed to form a fracture toughness master curve: K_{IC} versus $1/(a_T\dot{\varepsilon})$.

1. Introduction

Most semi-crystalline polymers display considerable ductility at room temperature. Nevertheless, in these materials a brittle failure easily occurs under low-temperature or high strain-rate conditions without large-scale yielding. To calculate rapid crack fracture toughness, linear fracture mechanics may be applicable by using the K_{IC} parameter. The previous attempt [1] to propose criteria based only on temperature dependence $K_{IC}(T)$ was not satisfactory for most semi-crystalline thermoplastic materials. The identification of a shift factor, a_T, calculated from an experimental study of the yield stress, σ_s, as a function of the temperature, *T*, and strain rate, $\dot{\varepsilon}$, enables the plotting of a master curve of the fracture toughness $K_{IC} = f(1/a_T\dot{\varepsilon})$ against reduced strain rate. A critical value $(a_T\dot{\varepsilon})_c$ is proposed to limit the validity of the linear elastic fracture mechanics (LEFM) analyses.

2. Experimental procedure

2.1. Strain rate–temperature equivalence

The time–temperature superposition principle has been found to be extremely successful for a large variety of polymers, even though it is quantitatively correct over limited time–temperature ranges for linear viscoelastic regimes [2]. In the literature, (see, for example, [3, 4]), results for K_{IC} (or G_{IC}) obtained at different temperatures are superposed by using experimental shift factors to form a master curve of fracture toughness versus reduced strain rate, $a_T\dot{\varepsilon}$. Furthermore, Massa [5] reported a comparison between the experimental shift factors and the results calculated by applying the Williams–Landel–Ferry WLF equation [2] and discussed this in the case of two types of PE.

In a semi-crystalline medium density polyethylene (MDPE) used to extrude pipes for gas distribution (for this MDPE polyethylene $M_W = 150\,000$, $M_n = 18\,000$ with a crystallinity rate of 47%), the process zone ahead the crack tip depends on the yield stress, σ_s. Therefore, this threshold value for the plasticity is used in the present work to determine the shift factor, a_T.

Fig. 1 shows the tensile specimen geometry. The specimens were cut in the axial direction of the MDPE pipe. Constant crosshead rate tensile tests were conducted for a wide range of temperature ($-50\,^\circ$C, $+60\,^\circ$C). Prior to the test, the temperature was maintained for about 2 h.

Yield stresses, σ_s, are calculated as

$$\sigma_s = \frac{F_{max}}{S_0} \quad (1)$$

the maximum force/initial cross-sectional area corresponding to the yield point.

The tensile tests were carried out at different strain rates: $5 \times 10^{-4}\,s^{-1} < \dot{\varepsilon} = 50\,s^{-1}$
where

$$\dot{\varepsilon} = \frac{1}{L_0}\frac{\Delta L}{\Delta t} \quad (2)$$

(crosshead displacement rate/effective specimen length, L_0(50 mm)).

2.2. Rapid crack propagation tests

Rapid crack propagation (RCP) tests were carried out either on cracked-ring specimens tested in compression (Fig. 2) or on impact testing Charpy specimens (Fig. 3). A straight crack of initial length $a_0 = 2$ mm was inserted by using a cutter blade. The insertion of the crack was very critical and care was taken to ensure a sharp crack tip. In order to control the RCP regime in cracked-ring specimens, adhesive velocity gauges were applied across the crack path and the crack opening displacement was measured by a clip gauge extensometer.

Each geometry was tested at different strain rates. For cracked-ring specimens, $\dot{\varepsilon}$ = (load point displacement rate)/(ring diameter); $\dot{\varepsilon} = 0.015\ \mathrm{s}^{-1}$. For Charpy specimens, $\dot{\varepsilon}$ is calculated as the maximum bending strain rate in the arm. A small rubber pad at the striker place was used to reduce the oscillations; $\dot{\varepsilon} = 50\ \mathrm{s}^{-1}$.

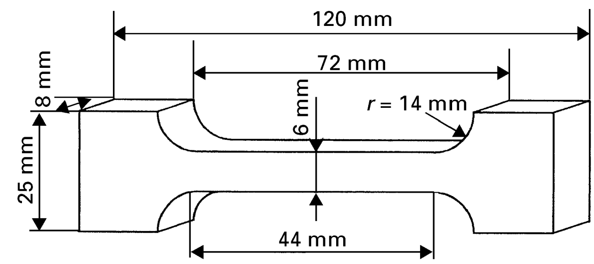

Figure 1 Dimensions of tensile specimens.

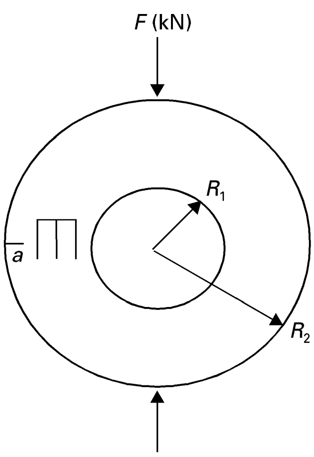

Figure 2 Ring specimen: geometry, loading and dimensions. $\beta = R_1/R_2 = 1/2$; $\lambda = a/(R_2 - R_1)$; $R_2 = 50$ mm; B = thickness = 15 mm.

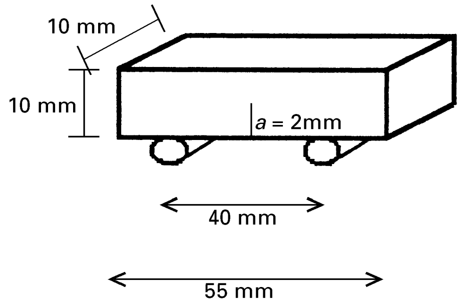

Figure 3 Dimensions of Charpy specimens.

The temperature range was (−100 °C, +20 °C). During the tests, loading versus time curves were recorded in order to reveal the initiation of the RCP which occurs after a short ductile slow crack growth stage. Therefore, from the load for rapid crack initiation, the corresponding fracture toughness, K_{IC}, can be calculated.

3. Results and discussion

3.1. Strain rate–temperature equivalence

In Fig. 4, experimental results are shown in a logarithmic plot. Eight $\sigma_s = f(1/\dot{\varepsilon})$ curves are given for a wide range of temperature (−50 °C, +60 °C). The reference curve corresponds to the lower temperature (T_R = −50 °C). The shift factor, a_T, is determined to perform the superposition of σ_s versus strain rate, $\dot{\varepsilon}$, curves. The superposition principle is mathematically expressed as

$$\sigma_s(T_R, 1/\dot{\varepsilon}) = \sigma_s[T, 1/(a_T\dot{\varepsilon})] \quad (3)$$

where the reference temperature $T_R = -60$ °C, and the current temperature is T. The experimental curves obtained at various temperatures can be shifted along the $\log(1/\dot{\varepsilon})$ axis in order to calculate the shift factor, a_T. For example, from the $\sigma_{s1} = f(1/\dot{\varepsilon})$ curve at $T_1 = -30$ °C (Fig. 4), we can find strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_R$ such that

$$\sigma_{sR}(T_R, 1/\dot{\varepsilon}_R) = \sigma_{s1}(T_1, 1/\dot{\varepsilon}_1) \quad (4)$$

By applying a multiplicative factor, a_T, to the $1/\dot{\varepsilon}$ axis, i.e. an additive factor to the $\log(1/\dot{\varepsilon})$ axis, one can calculate the shift factor, $a_T(T_1)$, such as

$$\begin{aligned}\sigma_{sR}(T_R, 1/\dot{\varepsilon}_R) &= \sigma_{s1}(T_1, 1/\dot{\varepsilon}_1) \\ &= \sigma_{sR}[T_R, 1/(a_T(T_1)\dot{\varepsilon}_1)] \quad (5)\end{aligned}$$

This shifting procedure has been applied in the temperature range [$T_R = -50$ °C, $T_1 = -30$ °C $\cdots$ $T_7 = +60$ °C] to other $\sigma_s = f(1/\dot{\varepsilon})$ curves (see Fig. 4), in such a way that the shift factor, a_T, was determined as a function of temperature T for the same MPDE. Figure 5 shows the semi-logarithmic plot of the shift factor a_T, versus $1000/T$ (K). This plot is a convenient means of studying the relationship between the deformation mechanisms and the mechanical behaviour

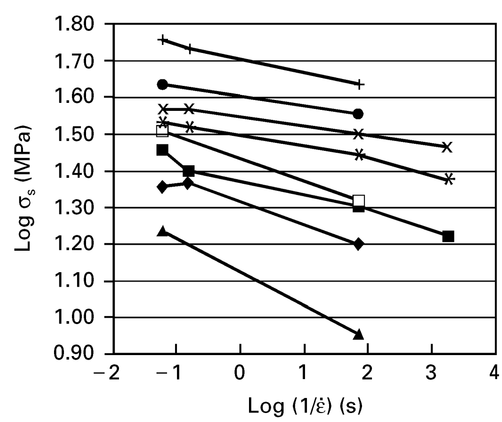

Figure 4 Logarithmic plot of the yield stress, σ_s versus $1/\dot{\varepsilon}$. T: (+) −50 °C, (●) −30 °C, (×) −10 °C, (∗) 5 °C, (□) 12 °C, (■) 20 °C, (◆) 35 °C, (▲) 60 °C.

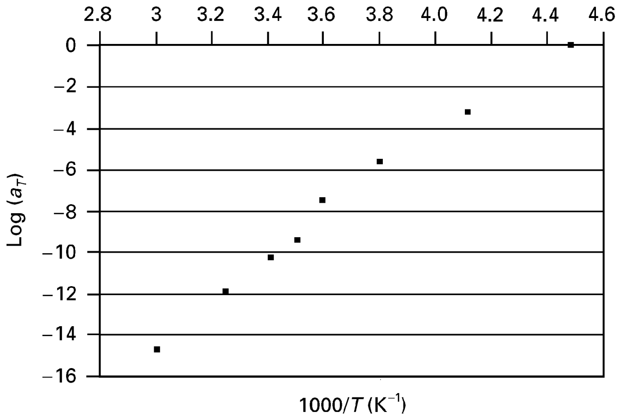

Figure 5 Semi-logarithmic plot of the shift factor, a_T, versus $1000/T$(K).

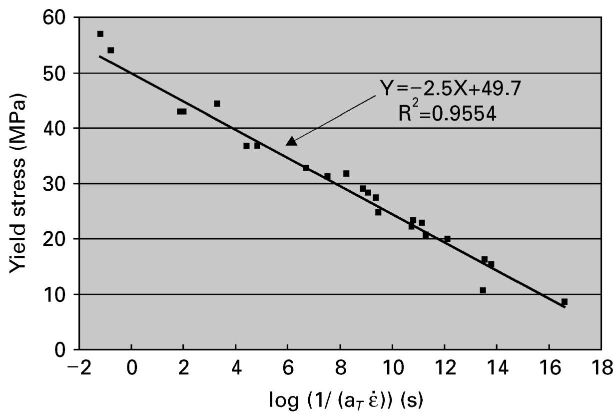

Figure 6 Semi-logarithmic plot of the yield stress, σ_s, versus $1/(a_T\dot{\varepsilon})$.

[5]. The semi-logarithmic plot of the yield stress σ_s versus $1/(a_T\dot{\varepsilon})$ shown in Fig. 6 indicates that an exponential law correlation exists between σ_s and $1/(a_T\dot{\varepsilon})$ in the ranges of strain rate and temperature considered.

3.2. Rapid crack propagation tests

The experimental initial conditions of Rapid Crack Propagation (RCP) tests performed on cracked ring and Charpy specimens are respectively given in Tables I and II. The crack lengths at RCP initiation stage were determined by fracture surface measurements. In these tables we have also included $\log(1/a_T\dot{\varepsilon})$ and the fracture toughness K_{IC}. The RCP velocity could be measured on cracked ring specimens, the range of initial velocity is [$150\,ms^{-1}$ to $350\,ms^{-1}$]. These values depend on initial test conditions, but they remain lower than the effective upper bound proposed by Kanninen *et al.* [6], i.e., $475\,ms^{-1}$ for our MDPE.

The fracture toughness $K_{IC}(T)$ curves were based on stress intensity calculations corresponding to the initiation of the RCP regime. In that case, the process zone (viscoplasticity and damage) at the crack tip is very small; linear elastic fracture mechanics (LEFM) may be applicable. The stress intensity factors, K_I, of impact testing Charpy specimens were calculated according to the ESIS protocol [7]. In the case of cracked-ring specimens, K_I calculations were performed on two-dimensional FEM ZEBULON code developed in Centre des Materiaux, Ecole des Mines de Paris [5]: the normalized stress intensity factor results are given in Table III, and the bell-shaped function, $K_1 = f[a/(R_2 - R_1)]$ with $R_1/R_2 = 1/2$, $R_2 = 50$ mm, $B = 1$ mm, and $F = 1$ kN is shown in Fig. 7.

TABLE I Initial conditions and results of rapid crack propagation tests performed on cracked ring specimens with a strain rate of $0.015\,s^{-1}$

Ring	$a/(R_2 - R_1)$	T (°C)	F (kN)	$\text{Log}(a_T\,\dot{\varepsilon})$	K_{IC} ($MPa\,m^{1/2}$)
1	0.38	−40	12.8	3.4	3.9
2	0.34	−50	11.6	1.82	3.8
3	0.35	−50	13.0	1.82	4
4	0.34	−50	11.6	1.82	3.7
5	0.36	−50	13.1	1.82	4.1
6	0.29	−60	12.5	0.22	3.9
7	0.27	−60	13.0	0.22	4
8	0.3	−60	13.1	0.22	4.1
9	0.26	−80	14.4	−2.98	4.4
10	0.25	−100	15.2	−6.4	4.6

TABLE II Initial conditions and results of rapid crack propagation tests performed on Charpy specimens with a strain rate of $50\,s^{-1}$

Charpy	a/W	T (°C)	F(N)	$-\text{Log}(a_T\,\dot{\varepsilon})$	K_{Ic}($MPa\,m^{1/2}$)
1	0.29	20	534	8.56	2.85
2	0.35	20	526	8.56	2.91
3	0.3	20	572	8.56	3.08
4	0.33	5	712	5.8	3.92
5	0.32	5	696	5.8	3.81
6	0.32	−5	758	4.5	4.15
7	0.33	−5	757	4.5	4.17
8	0.33	−15	780	3.3	4.29
9	0.32	−25	760	2.1	4.36
10	0.33	−35	817	0.7	4.50
11	0.29	−35	875	0.7	4.45
12	0.23	−60	860	−3.3	4.37
13	0.28	−60	898	−3.3	4.27
14	0.24	−80	828	−6.5	4.19
15	0.22	−80	880	−6.5	4.40

For both cracked-ring and Charpy specimens, the fracture toughness, K_{Ic}, versus temperature, T, are respectively plotted in Fig. 8. For the ring tests (Fig. 8; $\dot{\varepsilon} \approx 0.015\,s^{-1}$), the $K_{IC}(T)$ curve gradually and linearly decreases between $-100\,°C$ and $-45\,°C$. Above $-45\,°C$, a transition occurs in the slope, and it is not possible to initiate a brittle fracture. So, the linear fracture mechanics are no longer valid. More details (fracture surfaces and global loading versus time curves) are given elsewhere [5]. Under these experimental conditions, the transition temperature is defined by $(T_c)_{Ring} = -45\,°C$. Even though the impact testing strain rates are about 3300 times higher than the ring test ones, the shape of the $K_{IC}(T)$ Charpy curve is similar (Fig. 9). Nevertheless, it is not surprising to observe the transition in the slope at higher

TABLE III Normalized stress intensity factor, k_I, calculations of the cracked-ring specimen as function of relative crack length $a/(R_2 - R_1)$ with $R_1/R_2 = 1/2$, $B = 1$ mm, and $F = 1$ kN. $K_I(\text{MPa mm}^{1/2}) = F(\text{kN})k_I[a/(R_2 - R_1)]/[B(\text{mm})\ R_{1/2}(\text{mm}^{1/2})]$

$a/(R_2 - R_1)$	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0	0	260.2	364.6	440.8	502.6	556.6	604.6	645.8	682.1	716.4
0.1	749	780	807	833	856	878	897	916	932	947
0.2	955	974	986	996	1006	1015	1023	1030	1036	1041
0.3	1050	1050	1053	1055	1057	1057	1057	1056	1055	1052
0.4	1049	1044	1038	1031	1024	1015	1005	994	982	968
0.5	952	937	920	901	880	858	835	810	783	755
0.6	726	693	659	623	586	546	505	461	416	368
0.7	318	265	211	153	94	–	–	–	–	–

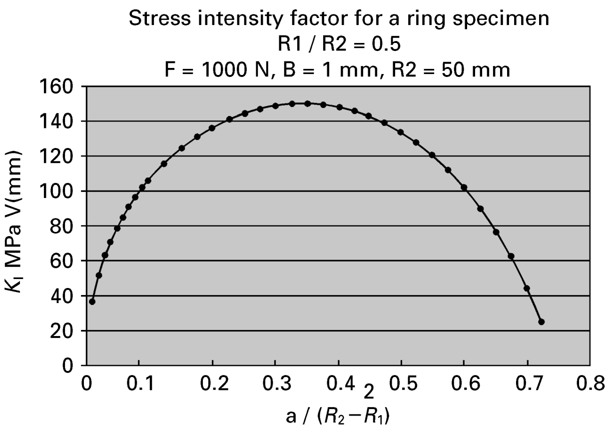

Figure 7 Ring specimen stress intensity factor, K_I, versus normalized crack length $a/(R_2 - R_1)$ with $R_1/R_2 = 1/2$, $R_2 = 50$ mm, $B = 1$ mm, and $F = 1$ kN.

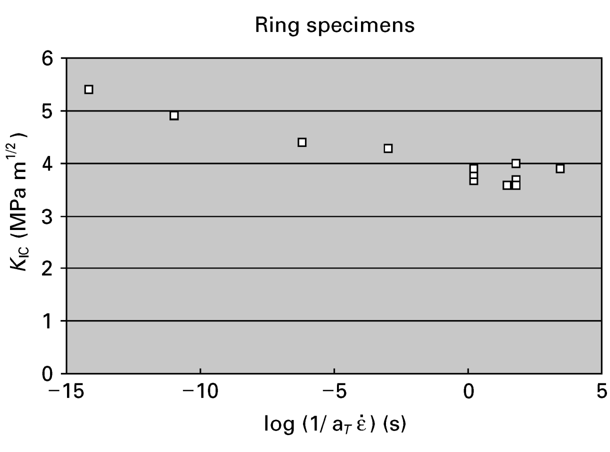

Figure 8 Fracture toughness, K_{Ic}, versus temperature, T for ring specimens.

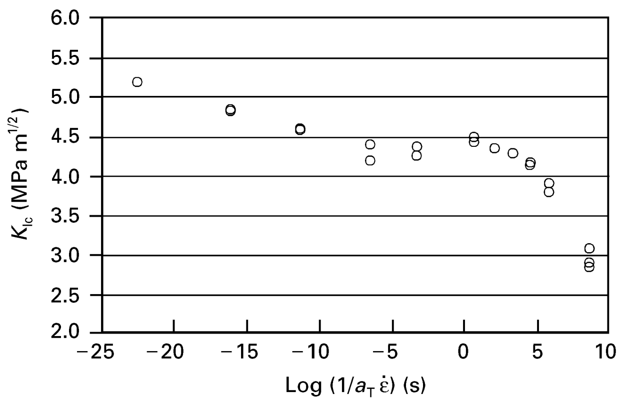

Figure 9 Fracture toughness, K_{Ic}, versus temperature, T, for Charpy specimens.

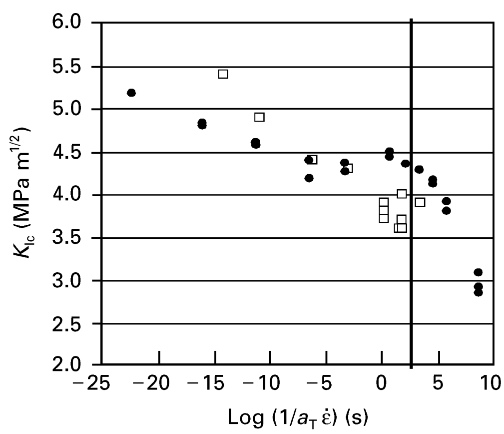

Figure 10 Fracture toughness master curve: K_{Ic} versus $1/(a_T\dot{\varepsilon})$. (□) Ring, (●) Charpy specimens; (——) criterion.

TABLE IV Transition values $(a_T\dot{\varepsilon})_c$

Specimen	T_c (K)	$\dot{\varepsilon}$ (s^{-1})	$(a_T)_c$ (s^{-1})	$(a_T\dot{\varepsilon})_c$ (s^{-1})
Ring	228	0.015	0.158	2.37×10^{-3}
Charpy	253	50	4.74×10^{-5}	2.37×10^{-3}

temperature: $(T_c)_{\text{Charpy}} = -20\,°\text{C}$. Above this temperature, the $K_{IC}(T)$ curve very rapidly decreases. It is related to the loss of the constraint of the crack tip process zone.

The introduction of the $a_T\dot{\varepsilon}$ parameter enables the plot of fracture toughness curves, K_{IC} versus $(1/a_T\dot{\varepsilon})$, to be made (Fig. 10). They are slightly specimen dependent, but we can calculate a unique and characteristic transition value $(a_T\dot{\varepsilon})_c$ for the investigated medium density polyethylene (Table IV). These results suggest that the mean values of the fracture toughness, $K_{IC} = f(1/a_T\dot{\varepsilon})$, might be an approrpriate master curve to predict the initiation of RCP regimes.

Below $(a_T\dot{\varepsilon})_c = 2.37 \times 10^{-3}\ s^{-1}$, the linear fracture mechanics are no longer valid.

4. Conclusions

1. The rapid crack propagation of a medium density polyethylene used to extrude pipes for gas distribution is studied in both testing conditions: cracked-ring specimens ($\dot{\varepsilon} \approx 0.015\ s^{-1}$), and Charpy specimens ($\dot{\varepsilon} \approx 50\ s^{-1}$), over a wide temperature range ($-100\,^{\circ}C$, $+20\,^{\circ}C$).

2. The identification of the shift factor, $a_T = f(T)$, calculated from an experimental study of the yield stress, σ_s, as a function of the temperature, T, and strain rate, $\dot{\varepsilon}$, is proposed to determine the relationship between the deformation mechanisms and the mechanical behaviour.

3. The introduction of the $a_T\dot{\varepsilon}$ parameter to plot the fracture toughness master curve as $K_{IC} = f(1/a_T\dot{\varepsilon})$ gives an appropriate criterion to predict the initiation of RCP regimes. A unique and characteristic value $(a_T\dot{\varepsilon})_c$ is proposed to limit the validity of such a curve for the investigated medium density polyethylene.

Acknowledgement

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