NEW MODEL FOR THE DUCTILE FRACTURE OF HIGH DENSITY POLYETHYLENE

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ABSTRACT

In this paper we present in a first part the use of J integral in describing the ductile fracture of HDPE and in a second part the development of a new model of damage growth at the crack tip during propagation.

KEYWORDS

Polyethylene - ductile fracture - damaged zone - Dugdale model - Rice integral - stress profile -

INTRODUCTION

Few papers has been published on the fracture of polymers in which the ductility prohibits the use of LEFM. Ferguson and al,(1973) have shown using the Dugdale model for the crazed zone of High Impact polystyrene, that the COD is an accurate fracture criteria. Recently Brown and al,(1979) in a study on the crack propagation have also described the plastic zone by a Dugdale model and the craze initiation stress may be evaluated.

Because of its extensive ductility, High Density Polyethylene (HDPE) has not been studied in fracture from notched specimen except in fatigue (Laghouati, 1977, 1979). Low Density Polyethylene has been studied in fatigue (Andrews, 1971) and in environmental stress cracking (Williams, 1976).

SAMPLE	60060	60130
DENSITY	0.959	0.955
MOLECULAR WEIGHT $\bar{M}_w$	150000	45000
CRISTALLINITY (%)	60	60
DEFORMATION AT BREAK (%)	1000	290
YOUNG MODULUS (MPa)	1220	1110
YIELD STRESS (MPa)	26	26

Table I
Structural and mechanical parameters

MATERIALS AND TESTING

The two HDPE used are described in table I together with their mechanical properties measured in a monotonic tensile test on ISO coupon. The main difference between the two samples is their molecular weight, thus giving to the sample 60060 higher ductility.

The fracture tests have been done on SEN sample (200 mm x 60 mm x 3 mm) from compression molded plates. The crack is initiated, from saw cut and razor notch, by fatigue. Monotonic tensile tests are conducted at a 0.5 mm/min. displacement rate. Observation of crack tip and damage propagation is made with photographs taken during the test.

Figures 1 and 2 show the load-displacement curves for a given initial crack length for the two HDPE together with the evolution of the crack tip aspect. There are clearly two phases : the first, before damage initiation, in which only visco-elastic and plastic deformation occurs around the crack tip (however for the 60060 a very small fatigue damage is observed) ; the second phase, where damage takes place and crack propagates and the third phase in which fracture (in 60130) or full yielding of the ligament (in 60060) occurs.

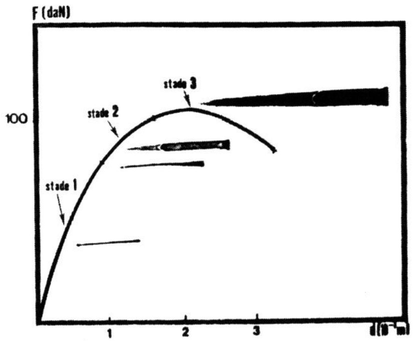

Fig. 1. HDPE 60130
Typical load-deflection curve

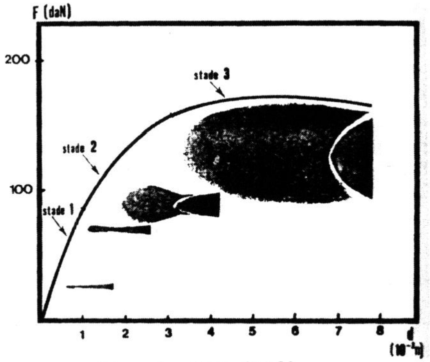

Fig. 2. HDPE 60060
Typical load-deflection curve

RESULTS AND DISCUSSION

We are interested in describing two stages of these experiments : the initiation of damage at the crack tip and the kinetics of damage growth. For the definition of a material parameter for the initiation point we have used the J integral in order to check the validity of a J_C criteria.

J_C as a damage initiation criteria

The evolution of J in function of the displacement d is calculated by the method of Begley and Landes with tests on various initial crack length. The results are shown on figures 3 and 4 for the two samples. The onset of damage is difficult to determine by visual direct photographic observation. This point was actually determined by extrapolating to nul damage a plot of damage length in function of displacement d. The J_C values obtained are :

60130 : $J_C = (1.0 \pm 0.25)\ 10^3\ J.m^{-2}$ 60060 : $J_C = (2.1 \pm 0.4)\ 10^4\ J.m^{-2}$

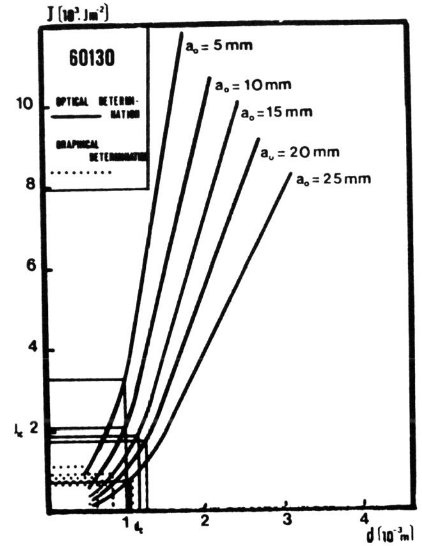

Fig. 3. HDPE 60130
J_C determination

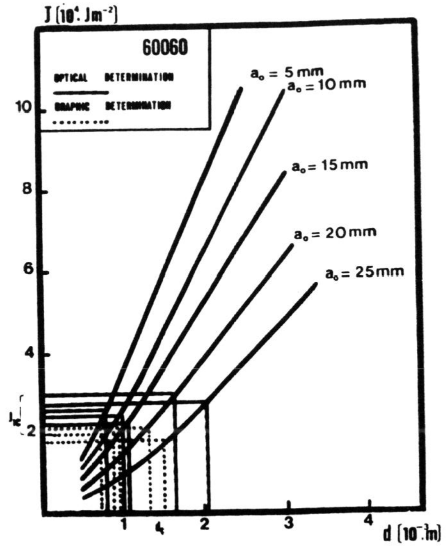

Fig. 4. HDPE 60060
J_C determination

The ratio of 1 to 20 between the two J_C values expresses the influence of molecular weight on the intensity of plastic deformation which should be spent before damage takes place. This high influence of M_W is to be compared with the influence of M_W on the G_C values measured by cleavage test on polymethylmethacrylate (PMMA). (Kusy, 1978). The J_C value for 60060 is higher than the G_C limit for infinite M_W PMMA.

The conditions for the thickness and the ligament length, which should be greater than 25 J_C/σ_y are verified for 60130. However this value is slightly lower than the ligament length for the 60060.

With this restriction, it appears that a J_C value is a good parameter (only materials dependent) for the definition of the damage initiation.

Damage growth

The J_C value is a very conservative fracture evaluation since crack propagation is preceded by a damage process which needs further energy.

A first approach to the description of the damaged zone is to use the classical models of plastic zone :

(Irwin, 1960) $\frac{1}{2}\ \frac{\sigma^2}{\sigma_y^2} = \frac{R/a}{1 + R/a}$

σ : gross stress
σ_y : yield stress
a : crack length

(Dugdale, 1960) $\frac{\Pi}{2}\ \frac{\sigma}{\sigma_y} = \text{Arc cos}\ (\frac{1}{1 + R/a})$ R : plastic zone length or damage zone length

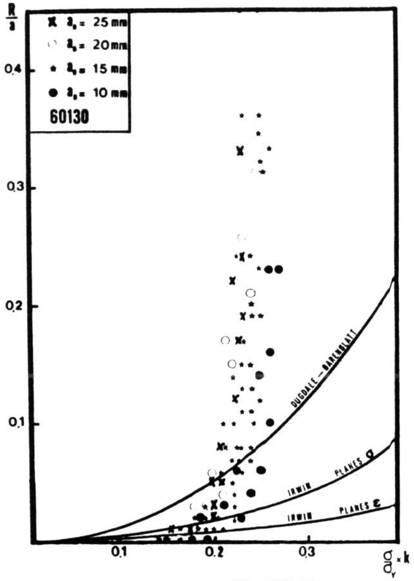

Fig. 5. HDPE 60130
Correlation with Irwin's
and Dugdale's models

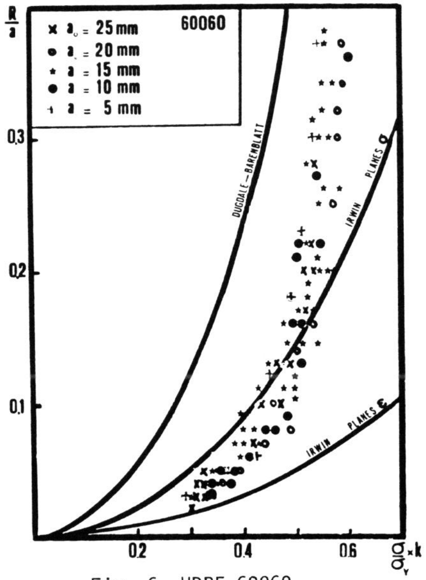

Fig. 6. HDPE 60060
Correlation with Irwin's
and Dugdale's models

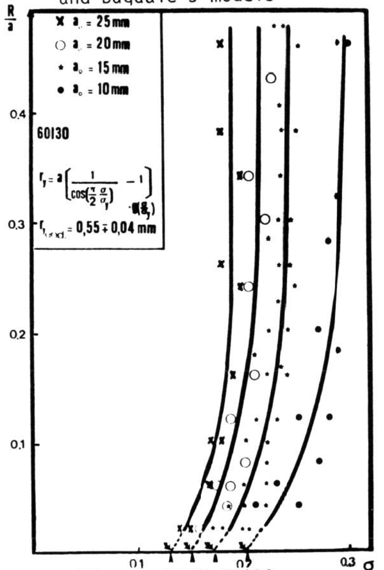

Fig. 7. HDPE 60130
Determination of damage initiation

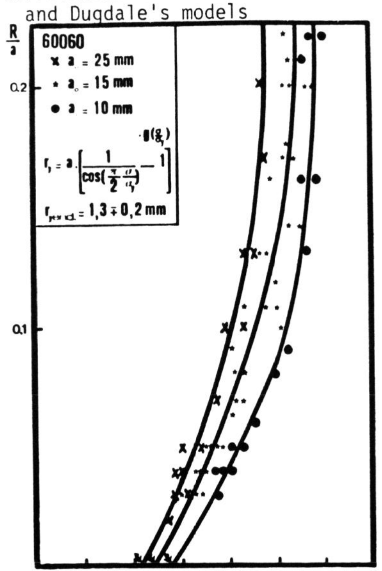

Fig. 8. HDPE 60060
Determination of damage initiation

The figures 5 and 6 show that these models do not describe correctly the damage length evolution. Not only the shapes of the curve are very different from the model but also the experiment shows that the damage takes place at a finite stress and does not start at zero stress as for a plastic zone.

Thus we have to take into account a plastic zone which precedes the damage zone. In order to check the validity of this hypothesis we measured by extrapolation (figures 7 and 8) the damage initiation stress and then we calculated the plastic zone size from the Dugdale model formula :

$$r_y = a\ (\frac{1}{\cos \frac{\Pi\sigma}{2\sigma_y}} - 1\ )\ g\ (\frac{\sigma}{\sigma_y})$$

where $g\ (\frac{\sigma}{\sigma_y})$ is the SEN correction factor (Tada, 1973).

60130 : $r_y = 0.58 \pm 0.04$ mm

60060 : $r_y = 1.4 \pm 0.2$ mm

Thus, for different initial crack length a_o , when the plastic zone size reaches a certain limit (material constant) damage initiates at the crack tip. This is consistant with the J_C constant value obtained for the damage initiation.

The plastic zone size for the initiation point has been directly measured by microhardness ahead of the crack tip on the 60130 sample (figure 9). The increase of microhardness is effective under 0.5 to 0.7 mm which is close to the calculated value (0.58 mm).

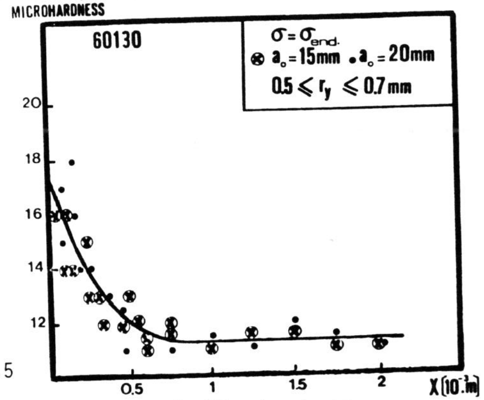

Fig. 9. Microhardness
ahead of the crack tip

Damage zone model

The crack tip zone is thus composed of two parts, a damaged zone which is easily observed and a plastic zone. We suppose that the plastic zone may be described, as Dugdale proposes, by a constant stress profile. For the damaged zone Gdoutos and al,(1974) have proposed various stress profiles in order to describe other material behaviour than the simple elastoplastic model. Their models are constructed with a set of small Dugdale model of various stress levels.

$$\frac{\Pi}{2}\ \frac{\sigma}{\sigma_y} = \text{Arc cos}\ (\frac{1}{1 + R/a}) + \frac{\sigma_{max} - \sigma_y}{10\ \sigma_y}\ \sum_m \text{Arc cos}\ (\frac{1 + m\ R/a}{1 + R/a})$$

$$- \frac{\sigma_{max} - \sigma_y}{10\ \sigma_y}\ \sum_n \text{Arc cos}\ (\frac{1 + n\ R/a}{1 + R/a})$$

σ_{max} , m and n defines stress profile and (Gdoutos and al, 1974) have proposed six profiles.

In the case of the low molecular weight sample (60130) the damage zone appears to be not homogeneous. Near the crack tip a few filaments link the two faces of the crack and the density of polymeric material increases throughout the damage zone. Then an increasing stress profile may represent correctly the damage zone. On the figure 10 we have presented the evolution of stress profile for the different stages of fracture. In the first stage plastic zone is growing until the damage takes place. Then the damage length R increases with applied gross stress :

$$\frac{\Pi}{2}\,\frac{\sigma}{\sigma_y} = \mathrm{Arc\ cos}\left(\frac{1}{1+\frac{R+r_y}{a}}\right) - \frac{1}{10}\sum_{m=0.1}^{0.9} \mathrm{Arc\ cos}\left(\frac{1+m\,R/a}{1+R/a}\right)$$

R : damaged zone length
σ_y : plastic zone size as calculated with Dugdale formula

The figure 11 shows the very good agreement between the model and the experiment for ratio σ/σ_y lower than 0.23 . Fast crack propagation occurs at a slightly higher ratio.

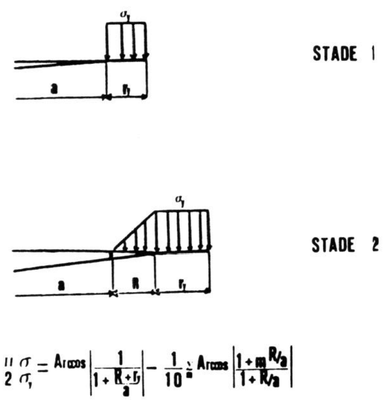

Fig. 10 HDPE 60130
Evolution of stress profile

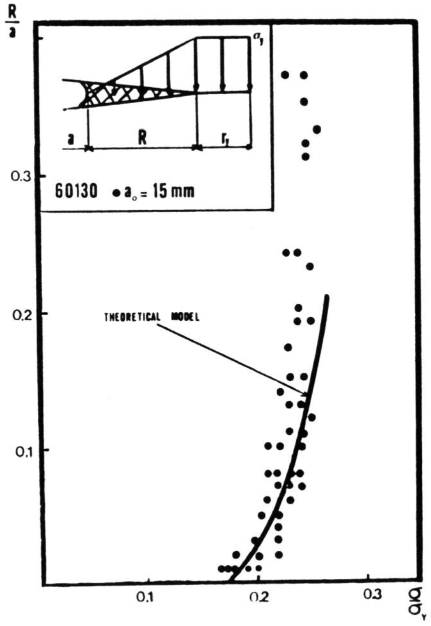

Fig. 11. HDPE 60130
Growth model of damaged zone

For the high molecular weight sample (60060), the damage zone is more homogeneous but there is a reduction of thickness near the crack tip. On the other hand strain hardening has an important effect for this sample. For these two reasons we have taken the profile n° VI Theocaris and Gdoutos which presents a stress increase near the damage zone tip and then a stress decrease. Figure 12 shows the evolution of the stress profile within the two stages of test. In the first stage, the plastic zone increases until damage takes place and then the damage zone grows in function of σ with a complicated relationship :

$$\frac{\Pi}{2}\,\frac{\sigma}{\sigma_y} = \mathrm{Arc\ cos}\left(\frac{1}{1+\frac{R+r_y}{a}}\right) + \frac{0.5}{10}\sum_{m} \mathrm{Arc\ cos}\left(\frac{1+m\,R/a}{1+R/a}\right) + \frac{0.5}{10}\sum_{n} \mathrm{Arc\ cos}\left(\frac{1+n\,R/a}{1+R/a}\right)$$

with m : 0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.45, 0.55
n : 0.80, 0.85, 0.95, 0.90, 0.90, 0.95, 0.95, 0.95, 0.95

$$\sigma_{max} = 1.5\ \sigma_y$$

Figure 13 shows the very good fit between the model and the experiment for ratio σ/σ_y lower than 0.55 ; general yielding of the ligament develops for higher ratio.

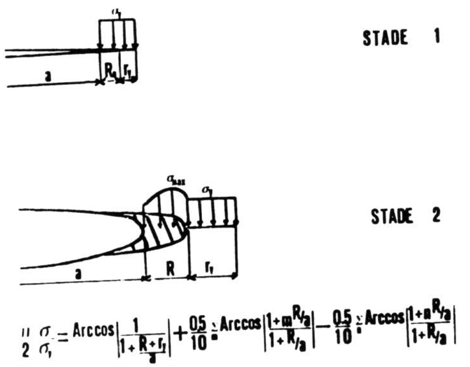

Fig. 12. HDPE 60060
Evolution of stress profile

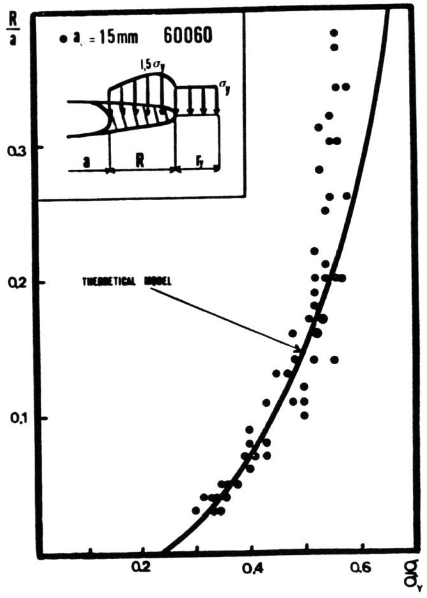

Fig. 13. HDPE 60060
Growth model of the damaged zone

CONCLUSION

In this study of fracture mechanics of HDPE we have shown that for these highly ductile materials it is necessary to take into account both stages of material failure : the plastic deformation and the damage accumulation.

At low stresses, a plastic zone is present around the crack tip and damage occurs for a given stress level. This damage initiation may be well characterized by a critical J_C value of the Rice integral.

The damage growth may be described by a stress profile which combines a plastic zone obeying Dugdale model and a damage zone in which the stress distribution takes into account the presence of microvoids (60130) or a strain hardening behaviour (60060).

This model which includes plastic zone and process zone may be very useful for several polymers in which the damaging (or processing) phase is an important phase of failures. The study of the mechanism of damaging of HDPE in such an experiment is now under progress (Rieunier, 1980).

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