SLOW CRACK GROWTH IN A MDPE : MECHANICAL BEHAVIOUR AND LONG TERM CREEP FAILURE PREDICTIONS

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Slow Crack Growth (SCG) behaviour was investigated in a medium density ethylene-butane copolymer (MDPE) on both axisymmetrical full notch crack tensile specimens (FNCT) under a constant load at 60°C and smooth gas pipes under a constant hydrostatic pressure at 80°C. Creep tests were carried out until fracture or interrupted. Crack advance process by discontinuous bands was observed in both cases. Besides, observations on a field scanning electron microscope (SEM) of several specimens coming from gas pipe creep tests have shown volumic damage. In order to take into account the SCG and this volumic damage in a creep damage law predicting long term failure, a behaviour law is needed. We have chosen a non-linear viscoplastic constitutive model and fitted it on the bases of experimental data issued from FNCT creep tests at 60°C.

INTRODUCTION

MDPE is being used increasingly as an engineering material for structural applications (extruded pipes for water and gas distribution). In these applications, the long-term performance and reliability have to be quantified in order to optimize the lifetimes. Consequently, a better understanding of the creep damage mechanisms is of prime importance. In parallel, a multiaxial constitutive creep law for the investigated MDPE is necessary in order to characterize the time-dependent crack tip stress-strain fields.

Many tests were developed to obtain SCG failures in short time. One such appealing procedure is the three-point bending test developed for the Gas Research Institute by Battelle (1). Using this technic together with the observation of the fracture surface in parallel with the analysis of the displacement of the load point as a funtion of time revealed that the SCG process was discontinuous, consisting of rather abrupt crack extensions followed by arrests. These discontinuities or arrest lines were also described by Chan and Williams (2) and referred to as a " Stick-slip mechanism" which they associated with crack blunting. Lustiger and Corneliussen (3) and Brown and Lu (4) also observed arrest lines in polyethylene. The latter authors explained the geometric features of discontinuous crack growth within the framework of the Dugdale theory (5).

To take into account this damage process, Popelar and al (6) have developed an engineering analysis model based on the principles of linear viscoelasticity which is strictly valid for materials with short craze lengths. This model estimates the crack length from the load point displacement record using a specific approch (see 7 and 8). But when long craze exist in the material, the non-linear viscoplastic behaviour can not be ignored. Various workers have investigated such non-linear viscoplastic behaviour (Ward (9), Bowden and al (10), G'Sell and Jonas (11), Kitagawa and al (12) and others ...).

The main objective of the present work is to provide a behaviour model including the

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creep damage process in order to predict the long term performance of MDPE structures. This work consists of two parts :

In the first part, in order to characterize the creep damage mechanisms, creep tests were operated at 60°C and 80°C on both FNCT specimens until fracture or interrupted and gas pipes under hydrostatic pressure. After the creep crack propagation tests SEM analysis was used to examine the fracture surfaces of the samples and their longitudinal sections around the crack tip. Therefore, the failure was observed at different stages.

Additionally a non-linear elastoplastic viscoplastic law taking into account both kinematics and isotropic hardening in the inelastic strain rate is proposed. The constitutive parameters were extracted from experimental creep tests carried out at 60°C on FNCT specimens. The results of such an identification are discussed.

In the last part of the paper, in order to propose a creep damage predicting model, we analyse the mechanical local parameters which can control the creep damage process.

EXPERIMENTAL PROCEDURE

FNCT specimens were cut directly from a MDPE 110 mm diameter gas pipe. The thickness of the pipe wall is 10 mm. The average density of the MDPE is 949 kg.cm^{-3}. It is an ethylene-butane copolymer with ~7 ethyl branches per 1000 carbons. The length direction of the specimen is the axial direction of the pipe. The notch was made by a fresh razor blade, its depth is 1 mm. A specific instrumentation was used to measure the load point displacement related to the creep notch opening of the specimen. The time for complete failure was also recorded. The scatter in the load point displacement measurement is within ± 15%. The tests were conducted at 60°C with the temperature being held constant within ±1°C. The specimens were subjected to a constant stress of 5,7 and 8 MPa based on the notched area. The side view of the damage zone was obtained by slicing the specimen along a meridian plane and then by viewing it with the SEM. The top view of the fracture surface was also observed with a SEM.

The second type of specimens consisted in gas pipe parts of about 1m long locked at their ends and creep tested under hydrostatic pressure of 9.6 bar at 80°C. Generally, the life time was limited by a leak of water due to the initiation and the propagation of a brittle creep crack through the pipe wall. Many small arc shaped specimens were then cut from the cross section of these pipes and fractured in liquid nitrogen. In the brittle fracture surface, the SEM observations show the creep damage zones.

EXPERIMENTAL RESULTS

Discontinuous Crack Growth

Fig.1 (side view) and fig.2 (top view) show the phenomenon of discontinuous crack growth. In fig.3, load point displacement is plotted versus time. Every jump in such a curve may corresponds to a forward step of the crack. The step depth increases with time. The first ones being so tiny that the corresponding jumps are not detectable on the curve fig.3.

The same kind of features are observable on a gas pipe specimen : fig.2-a shows a characteristic of a SCG initiated from a defect in the inner surface of the pipe wall.
Fig.1 shows, after etching, the morphological changes that are observed by viewing the

damage process from a side view. The fracture initiates within a craze growing from the root of the razor blade precrack.

SCG process could be explained by a competition between two mechanisms :

- a crazing process which takes place due to the highest principal stress acting in tensile direction at the crack tip.
- a micro-shear banding at the notch root.

Interaction between these two mechanisms stops momentarily the crack propagation and causes SCG by discontinuous bands.

Volumic damage

Fig.4 shows the fracture surface of a small arc shaped specimen taken from a cross section of a pipe creep tested at 80°C under hydrostatic pressure. In the brittle fracture surface, many circular damaged zones are located in the radial direction of the pipe (which is also perpendicular to the highest principal stress $\sigma_{\theta\theta}$ during creep). All the observations gave similar results. Therefore, we can conclude that all the pipe wall volume is creep damaged. Two zones in this creep damage "disc" can be distinguished :

- a central zone with fibrillated material similar to which is observed after a slow crack growth (fig.4-a) : it corresponds to the advanced stage of the damage.
- a second zone surrounding the first one resulting of microvoids (fig.4-b) : the less advanced stage.

INTERPRETATION

Both Lustiger and al (3) and Brown and al (4,5) have used a single edge notched specimen (SENT) in tension to study SCG in MDPE. In this work, we have chosen a full notched axisymmetrical specimen and showen that SCG occurs also in these conditions. Brown modelled the step depth using the Dugdale theory (5). We think that in the case of a viscoplastic material, the stress relaxation have to be taken into account. Also a crazing criterion seems to be more accurate to study SCG than a yield one. Further investigations should allow us to check the accuracy of these assumptions.

Whereas Brown (5) and Lustiger (3) used notched specimens to investigate SCG, we showed in the present work the existence of a volumic creep damage in the whole pipe wall. Such creep damage zone can initiate and propagate a creep crack up to the final fracture of the pipe.

The volumic creep damage can be explained by the disentanglement mechanism of tie molecules as reported by Brown and al (13). This mechanism could be inter or intraspherulitic depending on the relative strength of spherulitic and of its boundary (14).

It is not clear, for the moment, whether or not cavitation is involved as a precursor to the formation of the craze-like form at the crack tip.

BEHAVIOUR LAW

In order to modelise SCG in PE, a viscoplastic constitutive law is needed for the calculations of the time dependent stess-strain fields. Experimental and numerical studies carried out at Ecole des Mines de Paris, provided constitutive equations able to take into account plasticity, creep and creep-plasticity interactions for various inelastic mechanisms. The models are based on the classical decomposition of the inelastic strain into a time independent plastic strain and a time dependent viscoplastic strain.

G. Cailletaud and K. Saï (15) described with details this constitutive model commonly called "Double Inelastic Deformation" (DID) model. In this model, two mechanisms of deformation (plastic and viscoplastic) are considered. They are coupled by means of two kinematic variables. Furthermore, two flow criteria (plastic and viscoplastic yield surfaces) are postulated. In our case, we assume the plastic deformation to be negligible under creep loadings compared to the viscoplastic one. So we consider only elastic and viscoplastic deformations as follow :

potential gen_evp $\mathrm{J}(\underline{\underline{\sigma}}) = \sqrt{\frac{3}{2}\underline{\underline{\mathrm{s}}}:\underline{\underline{\mathrm{s}}}} \quad \underline{\underline{\mathrm{s}}} = \mathrm{DEV}(\underline{\underline{\sigma}})$

mises criterion $f = \left\langle J\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right) - R \right\rangle$ **; viscoplastic yield stress** R=Ro

flow norton $\dot{v} = \left\langle \frac{J\left(\underline{\underline{\sigma}} - \underline{\underline{X}}\right) - R}{K} \right\rangle^{n}$ **; kinematic nonlinear** $\begin{cases} \underline{\underline{X}} = \frac{2}{3} C \, \underline{\underline{\alpha}} \\ \underline{\underline{\dot{\alpha}}} = \underline{\underline{\dot{\varepsilon}}}_{v} - \frac{3}{2}\frac{D}{C}\underline{\underline{X}} \, \dot{v} \end{cases}$

C	K	Ro	poisson	n	D	young
50	48 MPa	1 MPa	0.4	4.45	0.5	478 MPa

The behaviour law is determined using three FNCT creep tests at 5, 7 and 8 MPa at 60°C. The identification of the parameters is made using an iterative inverse method which use an optimization loop of the F.E.M. Zebulon code. Results of this optimization are shown in fig.5. The chosen model and the experimental data are in good agreement.

Further work is needed in order to validate this law on other specimen geometry. The next step will be to model the creep damage process at initiation (volumic damage and propagation by discontinuous bands) with this viscoplastic constitutive law in order to predict the crack initiation stage under creep conditions.

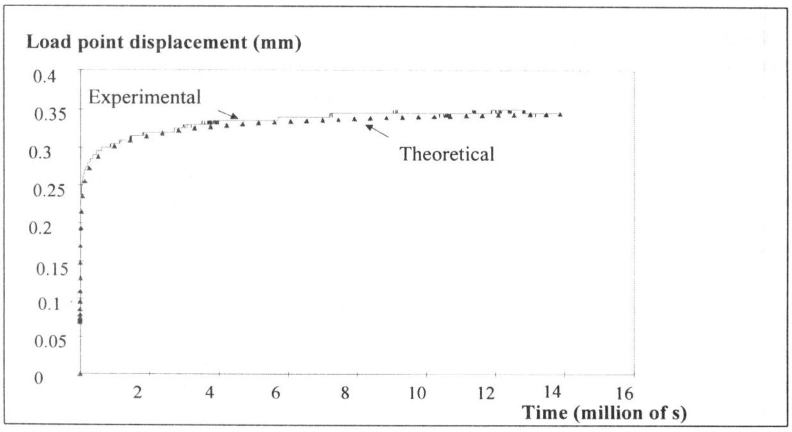

Fig.5- Experimental results and model predictions for a FNCT creep test at 60°C under 7 MPa.

CONCLUSION

- After creep, specimens are creep damaged in their whole volume.
- Volumic creep damage can initiate and propagate a creep crack by discontinuous bands up to the final fracture.
- SCG occurs for both cracked and uncracked specimens.
- A Double Inelastic Deformation model is suitable to describe the creep PE behaviour.

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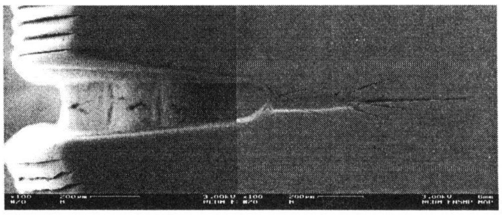


Fig.1- Creep damage at the crack tip : side view of FNCT specimen tested at 60°C under 8 MPa.

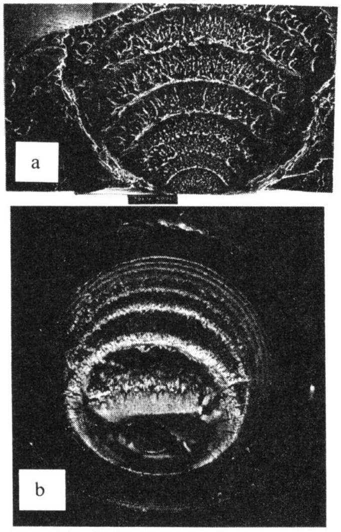


Fig.2- Fracture surfaces :
a- gas pipe creep failure.
b- FNCT creep failure.

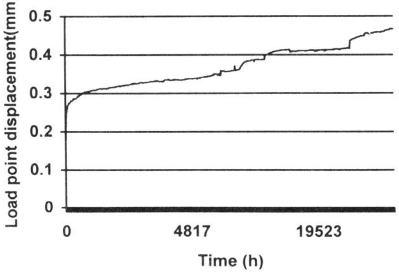
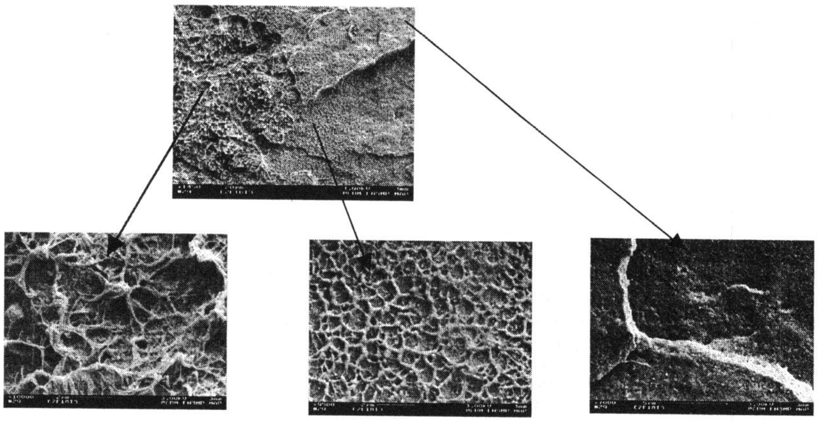


Fig.3- FNCT creep test at 60°C under 5MPa

Fig.4- Different zones of volumic creep damage :



a- Fibrillated zone : advanced stage

b- Microvoids zone.

c- Non damaged zone