RELATED EXPERIMENTAL AND MODELLING METHODS OF ANALYSING CRACK INITIATION AND PROPAGATION CONDITIONS IN POLYMER MATERIALS

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Résumé

Une méthode d'essai évitant le recours à un dispositif par impact a été conçue pour amorcer et faire propager une fissure dans un polymère. Elle est basée sur les bonnes propriétés d'isolation thermique des polymères et des matériaux équivalents, et sur leur tendance à se fragiliser lorsqu'ils sont refroidis à basse température. L'amorçage d'une fissure dans une partie fragilisée d'une éprouvette est un processus simple, et il est facile d'en assurer la propagation au sein même de la partie active de l'éprouvette qui peut avoir plusieurs géométries et présenter aussi des caractéristiques variées telles que la présence de joints adhésifs par exemple.

De la même façon on peut faire varier la contrainte de chargement de l'échantillon, selon les conditions réelles que l'on cherche à reproduire. Avec les dispositifs à choc qui s'appliquent à des éprouvettes de flexion trois points par exemple, ou encore avec d'autres conditions d'essais, il reste le problème de la détermination de la part prise par les forces transitoires lors du chargement dans l'initiation et la propagation de la fissure. Même si un appareil à choc débouche sur un essai très utile et réaliste, il peut être délicat de déterminer avec précision le point de rupture, ou d'autres spécificités auxquelles la méthode que nous proposons s'applique. Dans beaucoup de cas, l'essai par choc et la méthode proposée se complètent bien.

Abstract

A test method has been devised that initiates and propagates a crack in polymer materials that avoids the need of an impact device. This is to take advantage of the good thermal insulation properties of polymers and similar materials and their tendency to be embrittled when cooled to low temperatures. Crack initiation in an embrittled part of the specimen is a simple process and it can be arranged for the crack to then propagate into the main part of the specimen which can have a variety of different shapes and include bonded joints and other features. Also, the stress loading for the main part of the specimen can be varied to relate to the different conditions in which a material may be employed. With impact testers, that also apply dynamically a three-point bend or other test condition then a problem can be in determining how much the crack initiation and propagation is due to the impact transient forces relative to the three-point bending or other loading of the specimen. Although impact testing is a very useful and realistic test, it can be difficult to determine precisely the threshold of crack initiation and propagation and other key factors that the proposed test method achieves. In many ways, impact testing and the proposed method complement each other.

Introduction

With impact testers of the Izod or Charpy kind [1-4] it can be very difficult, if possible, to study one physical parameter of a polymer and consider it in isolation of all other properties. For example, many new high quality polymers, as well as having high resistance to crack propagation, can also have very lively dynamic responses such that impact testing of these materials can produce very difficult to interpret force-time records and other data. If all that is required, is to compare two different but similar materials by using identical test conditions, then, this may not be too much a problem. Often, however, much more other information is needed to arrive at the best choice of what can be a wide variety of different materials available to a product designer. These required data can be the transition from fast to slow crack propagation, extent of partial crack arrest, the degree of micro-ductility, side-lip tearing, visco-elastic effects and many others. Also, there can be a need to study crack propagation through welded and bonded joints and such features as may be needed in a product design. An experimental study is presented showing the dynamic behaviour of polymer specimens subject to high velocity impact tests. This is to explain, for example, how the strong transient vibrations can much contribute to the failure of the specimen and the effect of bounce of the specimen off the striker and support points [1-3]. Also, illustrated is the effect of reflections of the impact wavefronts from the ends of the specimen. This is to complicate determination of K_c and G_c and other needed derived data. Another type of testing[5] is then introduced which avoids some of the problems of impact testing but is complementary to it.

Experimental

Fig. 1. Force-time curves for fracture of pre-notched Charpy specimens (dimensions length L (65mm), width W (13mm) and breadth B (13mm)) at impact velocities of (a) 3.6 m s^{-1} (b) 3.04 m s^{-1} and (c) 1.3 m s^{-1} .

Fig. 2. (a) Test configuration. (b) striker sensor (c) $W/2 \times W/2$ sensor (d) $W/2 \times W/8$ sensor.

With Charpy types of test then as steady three-point bend forces are established, strong transient vibrations take the specimen to its failure point such as shown in Fig. 1. At the highest impact velocity, the force-time trace (Fig. 1(a)) shows a high-density polyethylene (HDPE) specimen failing on the third upward swing of the transients but before it has reached its peak. It is therefore difficult to determine precisely, the force and other conditions at this failure point and this is often the case. Bounce of the specimen off the striker and its supports will much complicate the transient forces. These affecting both reflections from the support points and the ends of the specimen. Although the transverse waves can be the more dominant ones, longitudinal, torsional and other waves can be excited if the specimen is not well centred in the Charpy test fixture. Fig. 2 shows the force-time traces as seen by a sensor on the striker and two sensors in different positions on an HDPE specimen. For routine testing when only a sensor on the striker is used, then on-specimen sensors may well be needed to initially validate the test [3]. These days, this can be more important than in the past because of the much improved dynamic response of new polymer materials as well as their better crack resistance.

It can be very difficult, if possible, to determine with impact testing a specimen's threshold loading for slow to fast crack propagation, the effects of visco-elasticity, side-lip tearing and other factors which can be very important to a product designer. Often, there is very much a need for a test when the specimen can be pre-loaded, allowed to stress relax and then have a crack induced into it without using an impact or other method that would excite unwanted transient vibrations to damage the specimen. A method has been devised using the good thermal properties of polymer materials [5] which is particularly convenient for evaluating sheet material.

Fig. 3(a) shows a prepared specimen of thickness 3 mm which has a protruding tongue extending the intended crack path through the specimen. This tongue of the specimen is rapidly cooled using liquid nitrogen or some other agent so that it can easily be cracked with a simple static three-point bending tool acting only through a very small angle of bend. The specimen is gripped at its two ends to extend the specimen and set up stress lines normal to the crack path. The extension jaws being fitted with a sensor to monitor the stress build up and then relaxation in the specimen after it has been extended. It follows that a wide range of tests can be carried out for different loading and stress relaxed loading levels before crack initiation. Fig. 3(b) shows a typical force loading curve and Fig. 3(c) a high-speed photographic sequence of the crack propagation. With a little practice, precise timing of the cracking event can be achieved well before the cooling of the tongue has reached the main section of the specimen.

Of course, the frozen-tongue technique does not generate the very noticeable crack initiation zone and hinge bend effects and the variation in side-lip tearing generated by the impact test methods. Generally, the frozen-tongue method produces cleaner, crack surfaces with a better distribution of micro-ductility and such features. Very important is that the frozen tongue technique makes it quite easy to determine the threshold for fast crack initiation and propagation and it is interesting to note how well these relate to theoretical models. Fig. 4(a) shows a least squares fit of experimental data to a Williams' model [6]. The flow of distributed strain energy into the crack surfaces is of much interest to designers and this is particularly so for thin sheets of material. Also, there is much interest in stress concentration at crack tips and the factors affecting the profile of the crack from the crack tip to the point when the fractured material is fully relaxed. The results shown in Fig. 4(b) and (c) were obtained by placing a strain gauge on the specimen adjacent to the crack path so that it would monitor the rise and fall of strain as the crack tip passed by the strain gauge. Strain gauges can be so deployed either side of the crack path and along its length to monitor any changes in the concentration of stress at the crack tip, changes in crack tip profile and crack tip changes as it passes from a thin to thick section of material and so on to a wide variety of possibilities.

Fig. 3. (a) HDPE specimen showing the height H (120 mm), width W (90 mm) and dimensions of tongue (20 mm x 30 mm). (b) Force-time trace for HDPE specimen fractured at stress relaxed load of 3.23 kN. (c) High-speed photographic sequence of crack propagation (velocity ca. 300 m s^{-1}).

Fig. 4. (a) Experimental data for HDPE specimens fractured using the frozen-tongue technique fitted to the Williams' model. (b) Strain gauge output for HDPE specimen (c) High-speed photographic sequence showing position of strain gauge labelled G.

Modelling

For some of the experimental work presented in this paper, the following shows the determination of K_c and G_c . For three-point bend specimens with a span to width ratio of $S/W=4$, as employed in these experiments, the following expression was used to determine the fracture toughness, K_c [4]:

$$K_c = (6P_c Y a^{1/2}) / (BW)$$

where P_c is the peak load at crack initiation, a is the length of the sharp pre-crack, B is the specimen thickness, W is the specimen width and Y is the finite-width correction factor. The fracture energy, G_c , was determined from [4]:

$$G_c = U_c / (BW\phi)$$

where U_c is the stored elastic strain energy in the specimen at crack initiation and the dimensionless geometry factor ϕ is given by $\phi = C / [dC/d(a/W)]$ where C is the compliance of the test specimen (i.e. displacement/load). A difficulty when determining G_c is to be precise about the energy absorbed by the specimen up to crack initiation because of the impact transients. Important can be the positioning of the sensors. For example, Table 1, which relates to Fig. 2, shows two sets of K_c and G_c values derived using the different outputs of sensors on the specimen and the sensor on the striker. For high impact velocities, it is to be noted that the K_c and G_c values as determined using the outputs from the on-specimen strain gauges and the strain gauge located on the striker differ greatly.

Table 1. Calculated values of K_c (critical stress intensity factor) and G_c (critical strain energy release rate) are tabulated above. K_c^{st} and G_c^{st} relate to the sensor on the striker and K_c^{sp} and G_c^{sp} relate to the sensors on the specimen in the $W/2 \times W/2$ and $W/2 \times W/8$ positions (see Fig. 2(a)).

Impact velocity ($m\ s^{-1}$)	P_c^{st} (kN)	P_c^{sp} (kN)	K_c^{st} ($MPa\ m^{1/2}$)	K_c^{sp} ($MPa\ m^{1/2}$)	G_c^{st} ($kJ\ m^{-2}$)	G_c^{sp} ($kJ\ m^{-2}$)
2	0.494	0.445($W/2 \times W/2$) 0.445($W/2 \times W/8$)	2.3	2.1 2.1	3.8	2.7 2.6
5	0.603	0.452($W/2 \times W/2$) 0.466($W/2 \times W/8$)	2.8	2.1 2.2	4.6	2.0 2.1

Table 2 shows the relation of crack velocity for different loading of polyethylene samples subjected to a frozen tongue test. In this case, the following gives the value of G_c [4]:

$$G_c = (P_o^2 H / 2EB^2 W^2) (B/B_n)^2$$

where P_o is the minimum stress relaxed load for fast fracture, E is the dynamic modulus of elasticity (2.2 GPa for high-density polyethylene (HDPE) and 1.8 GPa for medium-density polyethylene (MDPE)) and the factor $(B/B_n)^2$ is included because of side-grooves to ensure an in-plane fracture path in the specimen. From Table 2, it can be seen that for the HDPE samples, when the stress relaxed load was 2.45 kN, the crack only just severed the specimen. This minimum value of the stress relaxed load for fast fracture gives a G_c of ca. $5.0\ kJ\ m^{-2}$. Likewise, for the MDPE specimens, when the crack only just severed the specimen, this gave a G_c of ca. $7.2\ kJ\ m^{-2}$. As to be expected, the higher the loading of the specimen, the faster a crack will propagate when initiated (Table 2).

Table 2. Tabulation of the peak load, stress relaxed load and crack velocity for HDPE and MDPE samples tested using the frozen-tongue technique (* crack arrested).

Material	Peak load (kN)	Stress Relaxed Load (kN)	Crack Velocity ($m\ s^{-1}$)
HDPE	3.72	3.23	300
HDPE	3.23	2.65	160
HDPE	2.94	2.45	70.*
MDPE	3.14	2.94	80
MDPE	2.93	2.74	60
MDPE	2.74	2.65	40.*

It is interesting to link this experimental finding with a prediction model derived by Williams[6]. The expression for crack velocity, da/dt , in this lumped spring mass model is as follows:

$$da/dt = C_m [1 - (P_o/P)^2]^{1/2}$$

where P_o is the threshold load for crack propagation, P the stress relaxed load applied to the specimen and C_m is the maximum value of crack velocity attainable. Applying a least squares fit of the experimental data to the prediction model gives for HDPE, $P_o = 2.46\ kN$ and $C_m =$

439 m s⁻¹ (see Fig. 4(a)). This is to give a G_c of 5.1 kJ m⁻². This value needs to be adjusted depending on the thickness.

Using the frozen-tongue technique also provides for an interesting way of arriving at the stress concentration at the crack tip. For example, in Fig. 4(b), the on-specimen strain-time trace showed a rise of strain as the crack tip passed the strain gauge. This rise was in the order of 50%. The strain gauge was well away from the edges of the specimen so the distribution of stress would be near to that for an infinitely large specimen. The stress intensity factor K can be estimated from the Irwin stress function solutions using:

$$K = (1.5P / BW)(2\pi r)^{1/2}$$

where r is the distance of the strain gauge from the crack tip and the peak stress at the strain gauge is noted to be 50% greater than the mean stress. For the HDPE sample in Fig. 4, this gives a stress intensity at the crack tip of ca. 3.5 MPa m^{1/2}.

Conclusions

In the future, it is hoped to explore a variety of test conditions and relate these to the frozen-tongue technique so as to arrive at appropriate theoretical models using lumped mass spring constants. Also, to correlate the findings of different types of testing to resolve better the contribution to a specimen failure due to initial impact damage, transient vibrations of the specimen and the three-point bending or other steady state straining condition on which the test is based.

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