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Test method

High rate fracture toughness testing of thermoplastics

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ABSTRACT

To support the selection of polymers for applications subject to impact, industry needs an international standard method for evaluating high-rate fracture resistance. As another step towards establishing one, three generic thermoplastics were tested by five laboratories in a round-robin programme. Strain-gauged single edge-notched bend specimens of high density polyethylene, poly(vinyl chloride) and poly(methyl methacrylate) were subjected to impact at speeds from 0.2 to 27 m/s, and the crack tip loading time to fracture initiation, t_s, was measured. All three polymers indicated an inverse 4/3-power dependence of t_s on impact velocity, as predicted for an adiabatic decohesion mechanism — which is able to account for t_s in terms of bulk properties. Fracture toughness was calculated from failure time using a velocity dependent 'key curve' correction, assuming a constant elastic modulus. The scatter in toughness was significant, particularly for the more brittle materials, and appeared to be independent of test speed. The findings justify an emphasis on fracture initiation time as the primary measured parameter, and guide our proposals for further refining the method.

1. Introduction

Thermoplastic polymers are increasingly used for load-bearing machine components and for stressed structures such as pipelines. To predict and assess structural integrity, particularly in applications where there is a risk of rapid crack propagation, some measure of impact fracture resistance is required. It is rare, however, to find anything other than Izod or Charpy results or to see the limitations of those results fully recognised in the industrial world.

Under quasi-static conditions, a fracture energy or toughness result can be extracted from a fracture mechanics test by the analysis of measured load [1,2]. For impact at speeds of up to 1 m/s, a test method has been standardised (ISO 17281) in which damping pads between the striker and the specimen limit transient effects. The impact fracture toughness can then be determined in the conventional manner from the measured load at crack initiation [3,4]. However, at higher speeds the time to crack initiation is comparable with the period of vibrations excited in the specimen by striker impact. The resulting oscillations in the load signal make it impossible to accurately define its value at initiation.

It is possible to overcome some of these problems by using an analysis based on time to failure, rather than specimen load, and by applying a dynamic correction which accounts for some of the transient effects. One method has been proposed by Böhme [5–7] based on investigations with epoxy specimens in which caustics were used to determine the crack tip load. The basic assumption of this method is that the crack tip loading history $K_I(t)$ can

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be separated into a quasi-static part, $K_I^{st}(\phi)$ and a dynamic correction function, $K_I^{dyn}(t)$:

$$K_I(t) = K_I^{st}(\phi)K_I^{dyn}(t) \quad (1)$$

where ϕ is a dimensionless specimen compliance. The function $K_I^{dyn}(t)$ has been determined in various ways including model experiments [6], calculations based on mass-spring models [9,10] and numerical simulations [11]. The impact fracture toughness can now be evaluated as $K_{Ic} = K_I(t_f)$ by accurate measurement of the time to failure t_f. Other quantities must also be determined to apply this approach, namely the modulus and density of the material and (for the mass-spring model) the contact stiffness, as discussed below.

Technical Committee 4 of the European Structural Integrity Society (ESIS) directed an initial investigation of this approach, as reported by Böhme [8]. An initial round robin produced encouraging results but suggested that significant uncertainties had been introduced during pre-cracking of the samples, and that time to fracture (t_f) measurements had been insufficiently accurate. It was recommended that all specimens for the next round robin be prepared at a single laboratory and that t_f be measured using a more accurate method. For the present work these recommendations were taken into account in a revised draft test protocol. The results of a second round-robin are reported, and the measured failure times and their impact speed dependence are discussed in terms of an underlying adiabatic decohesion mechanism which emphasises failure time as a primary parameter [12–16].

2. Analysis

The quasi-static factor in Eq (1) is given by [8,10]:

$$K_I^{st}(\phi) = \frac{f}{\phi}\frac{E}{W^{1/2}}\frac{Vt}{(1+k^*)}, \quad (2)$$

where E is the tensile modulus (here assumed to be independent of time), V is the impact velocity and k^* the ratio of contact stiffness k_1 to specimen stiffness k_2. The geometry factor f was determined by Srawley [17] for a specimen span to width ratio $S/W = 4$ and any crack length $0 < a < W$, where W is the specimen width, it is given by

$$f = \frac{6\alpha^{1/2}\left[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)\right]}{(1+2\alpha)(1-\alpha)^{3/2}} \quad (3)$$

where α is the a/W ratio. The dimensionless specimen compliance ϕ is given by Bucci's [18] formula:

$$\phi = 0.24\left(\frac{S}{W}\right)^3\left(1.04 + 3.28\left(\frac{W}{S}\right)^2(1+\nu)\right) + 2\left(\frac{S}{W}\right)^2\alpha(4.21\alpha - 8.89\alpha^2 + 36.9\alpha^3 - 83.6\alpha^4 + 174.3\alpha^5 - 284.9\alpha^6 + 387.6\alpha^7 - 322.8\alpha^8 + 149.8\alpha^9) \quad (4)$$

where ν is Poisson's ratio.

The second factor $K_I^{dyn}(t)$ in Eq. (1) is a dynamic correction function which Böhme [7] determined in a model experiment by the evaluation of caustics. He expressed the result as a *dynamic key curve*, DKC, for a specimen having a relative initial crack length $a/W = 0.3 \pm 0.02$, relative specimen length $L/W = 5.50 \pm 0.10$ and relative support span $4.0 < S/W < 4.2$. For the range of failure times t_f addressed in this paper ($t_f < 9.2W/C_L$, where C_L is the longitudinal wave velocity in the specimen) it can be represented as

$$K_I^{dyn} = -0.9096 + 0.8176\left(\frac{C_L t}{W}\right) - 0.1005\left(\frac{C_L t}{W}\right)^2 + 0.003765\left(\frac{C_L t}{W}\right)^3. \quad (5)$$

Williams [9] has proposed an alternative approach based on a mass spring model. The test system is represented by a lumped mass model with the striker acting, through a contact stiffness k_1, on a specimen of stiffness k_2 and equivalent mass m equal to 17/35 of its total mass. The contact stiffness k_1 is a key parameter of the system dynamics. In reality, this factor is not independent of load but, for the current case of contact of a finite cylinder on a plane, it can be approximated as being so. Hence, the fracture toughness for a failure time t_f is given by

$$K_I(t) = K_I^{st}(t)\left[\frac{1 - \sin\omega t}{\omega t}\right], \quad (6)$$

where the natural frequency of the system is

Table 1
Physical properties of the materials used.

Material	PE	PVC	PMMA
Density, ρ (kg/m^3)	942	1469	1190
Modulus, E (GPa)	1.0	3.0	3.0
Melting temperature, T_m (°C)	140	250	–
Glass transition temperature, T_g (°C)	–	–	105
Mean specific heat, C_p (kJ/kg K)	3.5	0.9	1.45
Thermal conductivity, k (W/m K)	0.36	0.21	0.20
$V^{4/3}t_s$ from Eq. (9) (m$^{4/3}$ s$^{-1/3}$)	7.53×10^{-4}	5.80×10^{-4}	3.65×10^{-4}

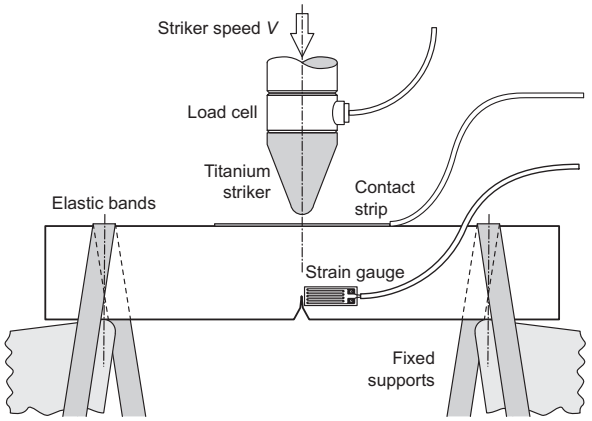

Fig. 1. Typical test setup showing contact strip, crack tip strain gauge and striker load cell. The setup is viewed from behind by high speed video equipment.