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Causes of scatter in high rate fracture testing of polymers

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ABSTRACT

A method based on the measurement of failure time is being developed by the European Structural Integrity Society to determine high rate fracture toughness of polymers. The test method appears reasonably straightforward but produced unacceptably high scatter, due to failure time data scatter. In this work an experimentally based sensitivity study was performed by fracture tests at 1 ms^{-1} in order to determine the causes of scatter and to seek to improve the test protocol. No single cause of scatter was identified but the quality and repeatability of the notching technique was identified as a major contributor.

1. Introduction

A specific protocol for determining fracture toughness of polymers at high loading rates (>1 ms^{-1}) does not yet exist, but is needed for two reasons: firstly, polymers are viscoelastic materials, therefore their properties are rate-dependent and must be measured at speeds characteristic of the in service loading; secondly because the dynamic effects causing oscillations in the load signal are not accounted for in existing lower rate test [1]. Dynamic effects can be controlled at moderately high loading rates by damping techniques, as suggested in the ISO 17281 standard, which allows measurement of fracture toughness of polymers at loading rates lower than 1 ms^{-1} [1]. At rates higher than 1 ms^{-1} approaches based on the loading record are unsuitable because most of the load is absorbed by the momentum, and the time to fracture is therefore comparable with the time taken by the stress waves to travel across the specimen, causing oscillations that make it impossible to define the point of fracture initiation.

To avoid the necessity of load measurement to evaluate fracture toughness, a methodology is being developed by Technical Committee 4 (TC4) of the European Structural Integrity Society (ESIS) which requires only the measurement of time to fracture. This approach is based on the dynamic key curves concept proposed by Böhme [2]. The basic assumption of the dynamic key curves method is that dynamic stress intensity factor, $K_{Id}(t)$, which is related to the real, dynamic crack tip loading, can be separated into a quasi-static part, $K_{st}(t)$, and a dynamic correction function, $k_d(t)$, which describes the influence of the transient dynamic effects, as shown by the following relationship:

$$K_{Id}(t) = K_{st}(t) \cdot k_d(t) \tag{1}$$

The quasi-static part can be analytically derived from a simple mass-spring model and calculated by the following equation:

$$K_{st} = \frac{f}{\varphi} \cdot \frac{E}{W^{\frac{1}{2}}} \cdot \frac{Vt}{(1+\frac{1}{\alpha})} \tag{2}$$

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Nomenclature

a	specimen initial crack length (mm)
DKC	Dynamic Key Curves
E	Young's modulus (MPa)
f	geometry factor according to Srawley
$k_d(t)$	dynamic correction function
K_{Ic}	fracture toughness (MPa $m^{1/2}$)
$K_{Id}(t)$	dynamic stress intensity factor (MPa $m^{1/2}$)
$K_{st}(t)$	quasi-static stress intensity factor (MPa $m^{1/2}$)
t	time (ms)
t_f	failure time (ms)
V	impact velocity (ms^{-1})
W	specimen width (mm)
α	ratio of contact stiffness to specimen stiffness
φ	Bucci's formula for dimensionless specimen compliance

where E is the Young's modulus, V is the impact velocity, t is the duration of the specimen loading, α is the ratio of contact stiffness to specimen stiffness, f is the geometry factor according to Srawley [3], W is the specimen width and φ is Bucci's formula for dimensionless specimen compliance [4]. The dynamic correction factor can be pre-determined in different ways: experimental [2], analytical [5] or numerical [6]. This term is represented by different functions, dependent on the loading device, specimen geometry and elastic modulus of the material, which in a normalized form are called dynamic key curves (DKC). If the proper dynamic key curve is known for the configuration used, K_{Id} value at fracture initiation (K_{Ic}) can be estimated by evaluating both terms, K_{st} and k_d, from the time to fracture, t_f, measured in a fracture test.

Two round robin testing activities have been carried out by ESIS TC4 to develop this approach. In the second of these test series, completed in 2008, a testing procedure was adopted in which the failure time was measured using the signal of a strain gauge placed near the crack tip. This activity was carried out on three different polymeric materials (PVC, PMMA and HDPE), by five laboratories, at various speeds ranging from 0.2 to 27 ms^{-1}. DKC based approach turned out to be a promising methodology, but its accuracy was weakened by a high degree of scatter in K_{Id} results, even in the relatively slow tests. This scatter existed both within data sets from individual laboratories and between the data sets of different laboratories so it could not be explained entirely by differences in equipment or technique. By analysing data of each single variable of Eqs. (1) and (2), time to failure results were identified as the most likely cause of scatter. Poor repeatability of results and the fact that data scatter was not velocity dependent suggested that a flaw in the experimental approach used for time measurement was more likely.

The aim of the present work is to determine the reason for the large degree of scatter affecting failure time results and, if possible, to provide recommendations and improvements which might be included in a further round robin activity. Several factors, possible sources of scatter, are investigated and an attempt is made to establish which factors influence the failure time measurements. In the present work an analysis of the procedure proposed in the round robin test for failure time measurement is shown, which is performed both by analysing results and measurements collected during the round robin activity and by performing tests on new specimens.

2. Experimental

The same testing procedure used for the second round robin activity and indicated in the protocol draft (see Appendix A in [6]) was adopted to perform tests on new specimens. The aim behind this was to recreate the same experimental conditions that led to the scattered results of the original round robin. The experimental details of the procedure, adopted in this work, are briefly described below. Any modification made in this work with reference to the draft protocol is highlighted.

The same polymeric materials used in the second round robin activity, PVC and PMMA, were tested. For that test specimens were centrally machined and notched, and then delivered to several laboratories for testing. In the current work the specimens were machined by the same institute and notched by similar notching techniques (but different operator). The tests were performed on machined Single Edge Notched in Bending (SEB) specimens of thickness 8 mm, width (W) 16 mm, length to width ratio 5.5, span to width ratio 4 and initial crack length to width ratio (a/W) 0.3. Dimensional tolerances of the machined specimen (width and thickness) were 0.1 mm for PVC and 0.05 mm for PMMA specimens. Notches were first machined, then sharpened (pre-cracked) by different techniques, due to the differences in pre-cracking behaviour between the materials. Notches in PVC samples were sharpened by sliding an industrial razor blade with a tip radius of 13 μm at the root of the notch (sliding technique), while notches in PMMA samples were sharpened by the wedging action of a blade tapped into the notch (tapping technique). Fig. 1 shows two examples of a typical pre-crack in a PMMA (Fig. 1a and c) and in a PVC sample (Fig. 1b and d). Fig. 1a and b are lateral views, while Fig. 1c and d show the fracture surfaces of tested samples. PVC pre-cracks were quite short (some tenth of millimetre) but the crack front was straight, while PMMA tapped