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Fracture mechanics testing for environmental stress cracking in thermoplastics

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Abstract

Under the combined influence of an aggressive environment and applied stress, engineering thermoplastics may undergo a phenomenon known as environmental stress cracking (ESC). This can result in adverse effects such as embrittlement and premature failure in service, due to the growth of environmentally-induced cracks to critical sizes, with little to no fluid absorption in the bulk material. Fracture mechanics is proposed as a suitable scheme to study and quantify ESC, with the aim being to obtain characterising data for different polymer-fluid combinations of interest, as well as to develop a reliable fracture mechanics test protocol. In the proposed method, slow crack growth is monitored to assess the effect of a range of applied crack driving forces (K, or alternatively G) on observed crack speeds, as opposed to simply measuring time-to-failure. This paper presents the results of experiments performed on the following materials: linear low density polyethylene (LLDPE) in Igepal solution and high impact polystyrene (HIPS) in sunflower oil. A discussion of the various issues surrounding the data analysis for these long-term tests is also included, as the attainment of consistent and repeatable results is critical for a method to be internationally standardised, which is a goal of the European Structural Integrity Society (ESIS) Technical Committee 4 from whose interest this work is drawn.

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Nomenclature

a	crack length
B	specimen thickness
C	specimen compliance
E	Young's modulus
G	strain energy release rate
K	stress intensity factor
P	applied load
S	span
W	specimen width
x	normalised crack length
Y	shape factor
δ	central deflection of specimen
ε	applied strain
ρ	notch tip radius

1. Introduction

Environmental stress cracking (ESC) occurs in certain thermoplastics when immersed in particular environments. In such cases, it is acknowledged that ESC is not due to bulk absorption of the environment, but rather is the result of the environment acting on an existing, loaded defect in the material, as noted by Williams (1984). ESC causes the incubation, initiation and resulting propagation of cracks leading to fast fracture of components, at applied stress levels significantly lower than normally required for the fracture of the material in air at quasi-static speeds. Incubation is defined here as the time between initial loading and the first instance of an increase in the crack length, i.e. crack initiation.

ESC has been investigated using several methods including chemical compatibility, time-to-failure, and strain hardening. The former for example, as in Hansen and Just (2001), has enabled the identification of polymer-liquid pairs having a higher tendency to stress crack as judged from the proximity of their solubility numbers. This allows the determination of polymer-liquid pairs which are inert and thus safe for mutual contact. The downside of these methods, however, is that they do not provide sufficient information for use as design criteria in the development of load-bearing components. Existing standards in usage, such as the Bell telephone (ASTM (2015a)), full-notch creep (ISO (2004)) and bent strip tests (ISO (2006)) tend only to provide a relative indicator of stress-cracking resistance; furthermore, they do not provide any information as to the mechanisms affecting the fracture rate of the material.

A fracture mechanics framework is thus considered suitable to study ESC phenomena, by loading notched specimens in environment and subsequently monitoring the rate of crack growth, i.e. crack speed under different levels of crack driving force (K, G). It was shown previously by Williams (1978) that unique relations exist between the crack driving force and crack speed, for any given polymeric material and temperature. An advantage of such tests is that they take shorter times than those measuring time-to-failure; in addition, the tests are able to distinguish between the different phases of crack growth, namely incubation, initiation and propagation.

2. Development of test method

The method adopted draws upon existing standards to measure K and G at initiation, such as for quasi-static plane strain fracture toughness (ISO (2000)). The specimen proposed is the single edge notched bend (SENB) configuration in three-point bend, as shown in Fig. 1. As with quasi-static fracture tests, the specimens are notched by razor sliding, taking care not to press the blade into the notch to avoid introducing residual stresses which may affect the test results.

The constant load (increasing G) set-up is a robust arrangement which allows for ESC testing across a wide range of applied crack driving forces, increasing from a fraction of the quasi-static fracture toughness (depending on the