

Characterisation of toughened polymers using fracture mechanics

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Abstract - A review of the principles of fracture mechanics will be given and in particular the use of K_c and G_c to characterise the toughness of polymers. The basic method is that of linear elastic fracture mechanics (LEFM) where in order to achieve plane strain a specimen size criteria must be met. These size requirements are quite large for many toughened polymers and LEFM cannot be employed. Smaller specimens can be used if the J_c method is employed and this will be described in some detail.

INTRODUCTION

The toughness of polymers is enhanced by many methods including the addition of a second phase, usually rubber, and sometimes a third phase such as fibres or particles are added to increase stiffness and strength. The resulting materials can have rather complex structures and the number of possible permutations is very large. In evaluating these systems it is essential to have meaningful measures of these characteristics in order that they may be optimised in some way or other. Traditionally the candidate materials are subjected to a battery of physical tests from which numbers such as tensile and flexural modulus, elongation, tensile strength, Izod number and Gardner impact values (to name but a few) are listed. The meaning of these numbers is often obscure though clearly the modulus reflects the stiffness and the other properties strength and toughness in some way. Just how they do is not clear and so any attempt at rational optimisation is unlikely to be effective.

The remedy to this situation, it is believed, is the use of properly defined material properties which are not functions of the particular test method used. For stiffness modulus is clearly such a parameter though the tensile and flexural values should be the same. If they are not then the system is inhomogeneous and should be characterised as such. For strength and toughness we must turn to Fracture Mechanics since this provides a rigorous framework in which these can be defined and thus can be put on the same footing as modulus.

FRACTURE MECHANICS PARAMETERS

Fracture toughness is defined as the energy per unit area required to create the fractured surfaces and in general is written as the fracture resistance R . This can be a function of rate and temperature as with other material properties and is also a function of the stress state in the material. It is lowest when the material is constrained and thus has a minimum of molecular mobility. The lowest practical case for this is *plane strain* when the deforming zone at the crack tip is prevented from contracting laterally and this is achieved if the plastic zone size is very much less than the other specimen dimensions. For this condition to hold the rest of the body behaves in an elastic fashion and one can use *elastic fracture mechanics* to analyse the fracture process. For linear materials we have linear elastic fracture mechanics (LEFM) which is the theory usually used but non-linear forms can be used as with elastomers. The driving force for the crack growth here is the release of elastic energy and this is termed G and when the crack grows this is equal to the energy dissipated, termed G_c and is R for the linear elastic case.

The most important case is that of a sheet subjected to a tensile stress σ containing a crack of length a . At fracture we have:

$$G_c = \frac{\pi \sigma^2 a}{E} \quad (1)$$

and this equation embodies the whole essence of fracture mechanics in that it specifies a stress level for a given flaw size and vice-versa. Notice also that it is based on energy since $(\sigma^2/2E)$ is the energy per unit volume remote from the crack. In fact the expression for G_c can be written in terms of the stored energy and is,

$$G_c = \frac{U}{BD\phi}$$

where U is the energy and ϕ a crack length dependent calibration factor. It is useful then to regard G_c as toughness since it is effectively the controlling factor in energy absorption.

The relationship can also be written as:

$$K_c^2 = EG_c = \pi \sigma^2 a$$

and here the parameter $K_c^2 = EG_c$ gives a measure of *strength* since it controls the stress levels. The interaction of G_c and K_c is via E , the modulus of the material.

The crack tip zone over which the energy is absorbed is given by:

$$r_p = \frac{1}{2\pi} \left(\frac{K_c}{\sigma_y} \right)^2$$

where σ_y is the yield stress and this length parameter is a material property so that there is not only a G_c (or K_c) but also a non-scaleable size effect which is crucial to understanding fracture.

APPLICATION TO TOUGHENED POLYMERS

This presentation will describe the use of these parameters to describe some toughened polymers including polystyrene and PVC. The toughening process gives decreased yield stresses whilst not changing K_c and r_p is fairly small (~ 1 mm). The plane strain, LEFM conditions can therefore be achieved easily with modest sized specimens and examples of the size effect will be given.

For the very tough polymers K_c increases, often σ_y is very low so that r_p becomes much larger (~ 1 cm) and then it is difficult to determine valid values of toughness. It is because of this change in relative size and thus stress state that confusing results occur so often in this type of testing. There is a scheme using a method called J-testing and this has been shown to overcome these problems by allowing much smaller specimens to be used. Examples of the method will be given for a medium density polyethylene and a toughened nylon.

It will be shown that these methods give a precise way of characterising materials and should be used in all characterisation. The possibility of a standard will be discussed.