A LINEAR ELASTIC FRACTURE MECHANICS (LEFM) STANDARD FOR DETERMINING K_C AND G_C FOR PLASTICS

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A review of the efforts of the Task Group on Polymers and Composites in producing a protocol for determining K_C and G_C is given. This is based on the ASTM metals standard E399 but significant variations have had to be introduced to account for the special properties of polymers, particularly visco-elasticity. Particular attention is given to notching, the detection of crack initiation and the determination of G_C.

INTRODUCTION

This is a report on one of the endeavours of the Task Group on Polymers and Composites chaired by myself and Professor Kausch. At the initial meeting of the Group it was decided that there was a considerable need in the plastics industry for a standard for K_C and G_C testing. Fracture Mechanics is now quite widely used for characterising the toughness of polymers and, to some extent, as a design method. Thus K_C and G_C values are frequently given in the literature but since there are no standards the values have either to be accepted at face value or supported by a large volume of information describing how they were obtained. Neither situation is satisfactory and some people use the ASTM metals standard E399 as a basis for the tests. This is helpful but not completely satisfactory since it is specifically designed for metals and many of its clauses are inappropriate to polymers and difficult to use. The Task Group has therefore set out to produce a testing protocol, based on E399, which will be suitable for use with polymers and, it is hoped, can be used for all standards in Europe. A parallel operation is also going on in ASTM using the same protocol so that the US standard will be the same.

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A third round-robin of tests is now in hand on what is hoped to be close to the final version of the protocol. If this current form proves to be satisfactory then it will be published. Here I will outline some of our experience and deal with the particular problems encountered in formulating a standard for polymers.

General Form

The protocol is strongly based on E399 and recommends the use of the three point bend and CT specimen. The specimen dimensions and loading rigs are identical to E399. There are problems in making large (>12mm) thicknesses in polymers because of low thermal conductivity and it is recommended that sheet thicknesses be used as specimen thickness (B). The following major differences from E399 are incorporated into the protocol.

Notching

Both metals and polymers require crack initiation from as sharp a crack as possible in order to ensure a minimum value of toughness. This is achieved in metals by using a fatigue crack which is induced at the notch tip. This is possible in polymers but in many cases is difficult experimentally and also is not necessary since a sufficiently sharp crack can be introduced by simpler methods such as machining or using a razor blade. In polymers showing brittle behaviour, and particularly thermoset materials, a natural crack is necessary and may be obtained either tapping a razor blade into the notch or fatiguing. For the softer polymers machining or sliding a razor blade will suffice. The recommended prodcedure is;

1) Make a sharp notched specimen by either machining or razor notching and obtain a provisional K_Q* value.

2) If $K_Q < 2\text{MPa}\sqrt{\text{m}}$ and/or the specimen shows particularly brittle behaviour in the form of a distinct triangular loading diagram then;

3) A natural crack must be used and may be obtained either by tapping a razor blade into the notch or fatiguing. (This is most commonly required for thermoset resins and the razor method is usually easier.)

4) If $K_Q > 2\text{MPa}\sqrt{\text{m}}$ and the loading diagram shows some curvature then the test may proceed with this form of notch. (The tougher materials appear to blunt the initial notch by plastic flow prior to failure and are thus less sensitive to the original form).

*The notation K_Q is used for a values whose validity is not yet established.

Test Conditions

Since plastics are viscoelastic materials it is necessary to specify both the temperature and time scale under which the result was obtained. As a basic test condition it is recommended that 23°C and a crosshead rate of 10mm/min be used. In all cases the loading **time** should be quoted.

If it is not possible to obtain valid results at 23°C it is often possible to do so by decreasing the temperature which usually does not change K_c greatly but increases the yield stress rendering the fracture more brittle. If this procedure is used then again both temperature and loading time must be stated.

It is recommended that speeds of greater than 1m/s or loading times of less than 1ms should be avoided because of the danger of dynamic effects causing errors.

Test Procedure

This follows E399 rather closely and uses the 5% compliance increase and/or maximum load as a fracture initiation criteria. The Pmax/P5% < 1.1 condition to limit non-linearity is also used. Considerable problems in defining initiation in polymers were encountered. Direct observations in transparent materials indicated that "something moved" at very low loads but for a practical standard the arbitary definition, which is equivalent to about a 2.5% growth in crack length, was considered to be a reasonable compromise. Calibration factors (Y^2) are taken directly from E399.

Size Criteria

Limits on B and W are imposed for two different reasons. That on B is to ensure plane strain crack tip stress conditions and hence a minimum K_c value while that on W is to avoid excessive plasticity and hence non-linearity. The E399 criteria of all lengths, i.e., B, W-a, a $> 2.5\,(K_c/\sigma y)^2$ has been shown to cover both of these quite satisfactorily for polymers, though it is perhaps somewhat conservative, and it has been adopted. It should be noted that σy should be measured at a similar time-scale to the fracture test and for polymers the stress at maximum load is appropriate.

G_c Determination

A major difference from E399 in the polymers document is the inclusion of a procedure for determining G_c. This is because G_c is used frequently for polymers, particularly when they are incorporated into fibre composites. In principle there should be no problem since G_c can be found from $G_c = K_c^2\,(1 - \nu^2)\,/\,E$ but the viscoelastic nature of polymers means that E must be carefully defined. Attempts to use separately determined E values in a round-robin series resulted in large variations and so it was decided that it would be better to measure G_c directly in the fracture test. In effect, of course, one is measuring E so that displacement must be measure and this involves all the problems of contact stiffness effects familiar in J_c testing. A separate test to correct for indentation at both the load and the supports is proposed and the G_c is to be found via the energy using either

$$G = \frac{U}{BW\phi} \qquad \text{or} \qquad \frac{\eta U}{B(W - a)}$$

where ϕ and η are(related) calibration factors. A cross check is suggested via compliance from which E may be found and hence G from the K^2 route. The method has not yet been confirmed and this is a major parameter in the current round-robin.

Conclusion

The general scheme of ASTM E399 works well for polymers but is is necessary to adapt the method to account for their special properties. The protocol produced by the working party has been partially tested and found to give consistent results. It will now be promoted throughout Europe and the US as an international standard.