A METHOD FOR DETERMINING CRACK VELOCITY STRESS INTENSITY CURVES FOR STRESS CORROSION CRACKING OF GRP

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ABSTRACT

Subcritical crack growth in the surface of Epoxy GRP, under acidic stress corrosion conditions was studied by a novel time-lapse micro-photograpical technique. The results were analysed using a LEFM theory applicable to elliptical surface flaws and found to be consistent with published data obtained from double cantilever beam experiments.

Keywords: Acidic stress corrosion cracking; GRP; epoxy; fracture mechanics.

INTRODUCTION

The majority of the previous work carried out on the stress corrosion of GRP has been of a qualitative nature and concerned primarily with identifying and characterizing the phenomenon. Whilst such work may produce short term answers to problems such as the life expectancy of a composite in static fatigue, the lack of depth and often physical significance of the tests carried out do not provide for the identification of the mechanisms involved. Thus for a further understanding of this phenomenon, it is essential to determine the factors that affect both crack initiation and subsequent subcritical crack growth. Accordingly, a fracture mechanics approach seems the most appropriate. The application of fracture mechanics to composite materials such as glass reinforced plastics is not an easy matter. The heterogeneity of the material coupled with its anisotropy results in extremely complex mathematical expressions, the validity of which are by no means proven. Most fracture mechanics studies of composite materials have ignored both the heterogeneity and anisotropy of the material, and used the theoretical approaches derived for homogeneous isotropic elastic continiums. The correctness of this approach is open to question, but until fracture mechanics can adequately describe the failure mechanisms occurring in composite materials there seems little option.

The results of previous studies on the stress corrosion cracking of GRP have firmly established that failure occurs by a brittle type of crack, which is quite unlike that found for a normal tensile failure (Rawe, 1962; Hogg and Hull, 1980, 1982; Jones and co-workers, 1982, 1983), where there is considerable fibre pull out, and splitting parallel to the glass reinforcement. Thus stress corrosion cracking appears to be more amenable to analysis by linear elastic fracture mechanics (LEFM) than the normal failure behaviour of a composite. This is especially true at the start of fracture,where microscopical studies of fracture surfaces (Hogg and Hull, 1980, Jones and co-workers, 1983) have shown that the area surrounding the stress corrosion crack initiation site is particularly planar. Moving away from this area the fracture surface becomes more irregular until eventually it takes on the characteristics of a pure tensile failure.

One of the experimental difficulties with measuring subcritical crack growth in a direction normal to the fibre reinforcement is maintaining the crack in this orientation to the fibres. Delamination along the fibre matrix interface may blunt the crack tip sufficiently to stop all further crack growth, in a direction normal to the reinforcement. Both Aveston and Sillwood (1983) and Price and Hull (1983) used double cantilever beam type specimens, grooved along the centre to provide a thin web of material through which the crack propagated. Whereas the former authors calculated the stress intensity (K_1) directly, the latter recorded the energy release rate (G_1) and then calculated K_1. Comparison between the separate results showed good agreement: Aveston and Sillwood attributed the increase in slope of their data with decreasing crack velocity to be indicative of a stress corrosion limit; however Price and Hull thought that this change in slope may be due only to a change in the mechanism of failure. They propose that at high values of K_1, resin cracking precedes fibre failure, but when K_1 is less than the toughness of the resin, fibre failure is required to increase the value of K_1 sufficiently for resin cracking to occur. It is this change in the order of events that could lead to a change in the rate of crack growth with stress intensity. Hogg and Hull (1982) studied the effect of resin toughness on stress corrosion resistance of composites. Although they did not use a fracture mechanics approach they did show that the mechanism of fracture changed with increasing resin flexibility. Both these studies used notched specimens and so could produce no information concerning the nucleation of stress corrosion cracks.

In this paper we describe a method which utilizes the growth of surface cracks, on unidirectional coupons under stress corrosion conditions, to obtain information on nucleation and subcritical crack growth. We feel this method has several advantages over that utilising double cantilever beam type specimens: there is no complicated specimen geometry and thus the production of test specimens is relatively easy, also since the cracks are self nucleated, factors which influence their nucleation can be studied.

EXPERIMENTAL PROCEDURES

The vacuum resin impregnation technique previously described (Jones and co-workers, 1983) was used to fabricate 0° unidirectional laminates. Epikote 828 cured with 80 p.h.r. Epikure NMA and 1.5 p.h.r. BDMA accelerator was used for the matrix resin, and Silenka 051P 1200 Tex E-glass roving as the reinforcement. An initial cure of 100°C for 3 hours was given to the laminate. Specimens, in the form of coupons of approximate dimensions 20 mm x 240 mm were cut from the laminate using a water cooled diamond wheel, and postcured at 150°C for 3 hours. Before testing, chromic acid etched aluminium end-tags were bonded to the coupons to prevent damage from the Instron grips.

0° unidirectional coupons were maintained under constant load either using an Instron Universal Testing Machine (1196) or Emec Creep Rigs. The aqueous sulphuric acid (0.5 M) was contained in a rectangular glass cell attached to the coupon by a split rubber bung. The nucleation and growth of stress corrosion cracks was recorded photographically using a Zeiss Tessovar microscope and attached camera. Photographs were taken automatically at regular time intervals dependent upon the applied load; typically for an applied stress of 210 MPa photographs were taken every 3 minutes. The number and size of the cracks were measured from enlargements of the photographs. To obtain a more detailed record of the stress corrosion cracks an automatic photomicroscope is nearing completion. This will allow for the storage, as x and y co-ordinates, of a number of locations on a specimen. At predetermined times the photomicroscope can be guided to the stored locations and record the stress corrosion cracking behaviour. This system will allow for a far greater coverage of the specimen than is possible with the fixed position "Tessovar" system.

RESULTS

The stress corrosion cracking behaviour of a specimen under a stress of 220 MPa (approximately 0.5% applied strain) is shown in Fig. 1. Difficulties in setting up the static photomicroscope precluded the taking of any pictures before 5 minutes after the application of the load. Thereafter photographs were taken every 3 minutes until total failure, which occurred shortly after 95 minutes and was consistent with previous data (Jones and co-workers, 1983). Considering the distribution and number of stress corrosion cracks growing 5 minutes after the load was applied, it seems that some form of predamage to the glass in the laminate surface is responsible for the nucleation of the majority of the stress corrosion cracks. Not all cracks nucleated

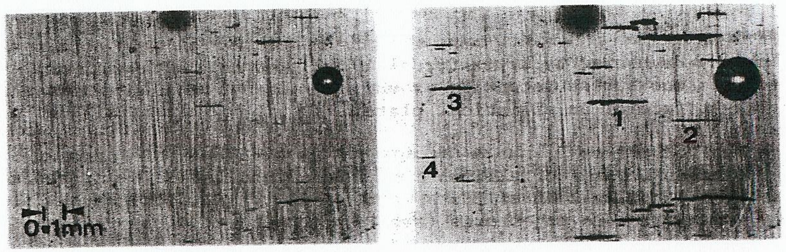

Fig. 1 Time-lapse photographs showing stress corrosion surface cracking in 0.5 M H_2SO_4 at constant load equivalent to an applied strain of 0.5%. The numbers refer to analysis in Fig. 4.

continue to grow, and of those that do, interference between neighbouring cracks, either in the form of coalescence or stress relief poses problems if any form of fracture mechanics approach is to be used.

Cracks formed by the coalescence of a number of smaller stress corrosion cracks are far more irregular in appearance and their usefulness for determining the toughness of the composite is expected to be limited. However since only one field of view was available from the static camera, their application was unavoidable. The cracks numbered in Fig. 2 have been used to calculate the variation of stress intensity with crack velocity in Fig. 4. Also included in Fig. 4 are results obtained from several fields of view, for cracks in which coalescence has not occurred.

DISCUSSION

The objective of this study was to determine the feasibility of using the growth of stress corrosion surface cracks to measure the material parameter K_1. It was intended to study the rate of nucleation of these cracks, but the limited amount of data available from the static photomicroscope was insufficient for analysis.

To a first approximation a stress corrosion surface crack may be modelled as an elliptical shaped surface flaw as shown in Fig. 2. The treatment of such flaws by LEFM has been extensive. In this study we use the theory developed by Irwin (Broek 1978), who derived equation 1 which predicts the stress intensity around the edge of an elliptical flaw in the surface of an elliptical plate.

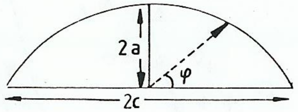

Fig. 2 An elliptical flaw with appropriate dimensions.

$$K_1 = \frac{\sigma(\pi a)^{\frac{1}{2}}}{\Phi} (\mathrm{Sin}^2 \phi + \frac{a^2}{c^2} \mathrm{Cos}^2 \phi)^{\frac{1}{4}} \qquad (1)$$

where σ = applied stress
a = semi major axis of ellipse
c = semi minor axis of ellipse
ϕ = angle from the major axis (see Fig. 3)

$$\Phi = \int_0^{\pi/2} (1 - \frac{c^2 - a^2}{c^2} \mathrm{Sin}^{-2} \phi)^{\frac{1}{2}} \delta\phi$$

Φ can be developed into a series expansion and even for angles approaching zero, neglect of the third term results in only 5% inaccuracy.

$$\Phi = \frac{3\pi}{8} + \frac{\pi a^2}{8 c^2} \qquad (2)$$

Equation 1 predicts that the value of K_1 is a maximum at the end of the minor axis and a minimum adjacent to the major axis. The implications of this are that in the absence of any other factors, elliptical flaws will grow towards a semicircular shape. The importance of this is discussed more fully later. In this study we are only concerned with the value of K_1 adjacent to the major axis, since this determines the rate of crack growth parallel to the surface, and this is given by equation 3.

$$K_{1(\phi = 0)} = \frac{\sigma}{\Phi} (\pi \frac{a^2}{c})^{\frac{1}{2}} \qquad (3)$$

For this equation to be applicable to cracks in a plate of finite size, certain corrections are necessary (Broek 1978); correction for the effect of the back free surface amounts to an increase in the value of K_1 by approximately 12%. The front free surface correction depends upon the crack aspect ratio, and also the ratio between crack depth and plate thickness. By considering only small surface cracks and assuming an aspect ratio of no greater than 2:1 this correction becomes minimal and will be ignored in this work. A further correction for plastic deformation at the crack tip may also be applied to equation 3, resulting in equation 4.

$$K_{1(\phi = 0)} = 1.12 \sigma (\pi \frac{a}{Q})^{\frac{1}{2}} \qquad (4)$$

where Q is known as the shape parameter and contains the plastic deformation correction

$$Q = (\Phi^2 - 0.212 \sigma^2/\sigma^2_{ys})^{\frac{1}{2}} \qquad (5)$$

where σ_{ys} is the yield stress

The magnitude of this correction depends upon the ratio of the applied and yield stresses. Assuming the yield stress of a composite material to be near to the fracture stress, then $\sigma/\sigma_{ys} - 1$ and which produces only a small error in Q.

From equation 1 it can be seen that the value of K_1 is dependent on the aspect ratio of the crack which is shown graphically in Fig. 3. To be able to use equation 4 certain assumptions about the aspect ratio must be made. If it is assumed that the failure of a single glass fibre initiates a stress corrosion crack, whose aspect ratio will depend on how far the fibre is embedded into the surface. A fibre that is completely embedded will result in a crack of aspect ratio less than 1 whereas partially embedded fibres will give aspect ratios greater than 1. Since optical examination of the surface of a composite shows that fibres are generally embedded at least half way in the surface, the lower bounds of the aspect ratio is 2. It was stated above that an elliptical crack will grow towards a semicircular shape. Therefore the flaw will grow, with an aspect ratio that will not vary appreciably

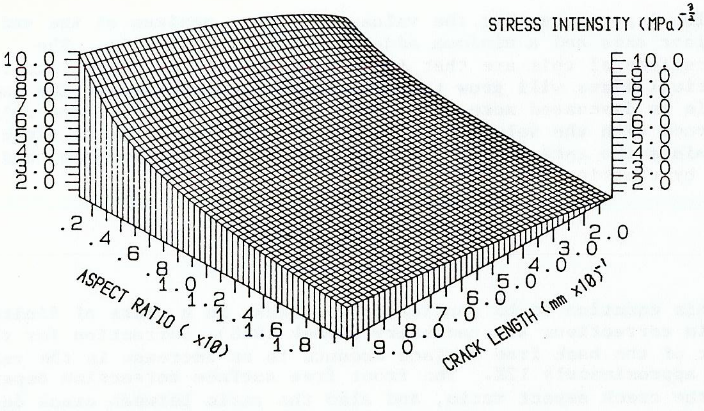

Fig. 3 The stress intensity of an elliptical flaw with varying aspect ratio.

from 1. If the aspect ratio did not tend towards this value, it would be exceedingly difficult to use equation 4.

It has been found that the crack growth rate is related to the stress intensity as shown by equation 6.

$$\frac{\delta a}{\delta c} = \alpha K_1^{\,n} \qquad (6)$$

where $\delta a/\delta c$ = Flaw Growth Rate
K_1 = Stress Intensity Factor
α, n = Constants

from a logarithmic plot of the rate of crack growth against the stress intensity, straight lines of slope n are expected. Such a plot is shown in Fig. 4. Also shown are the results obtained by Aveston and Sillwood (1983), and Price and Hull (1983), using double torsion beam techniques. The greater scatter in our results when compared with those of Price and Hull can probably be attributed to local variations in volume fraction which would significantly affect the crack growth rate for similar stress intensities. Also there are complicating problems when cracks coalesce. This produces a large increase in the aspect ratio, with a corresponding decrease in the value of k_1, which manifests itself as a fall in the crack growth rate. No attempt has been made to estimate a value for n, since the data is considered to be insufficiently precise. However these results are consistent with a previous study, where it was observed that the stress corrosion resistance of the epoxy was considerably lower than that of a polyester composite (Jones and co-workers, 1982).

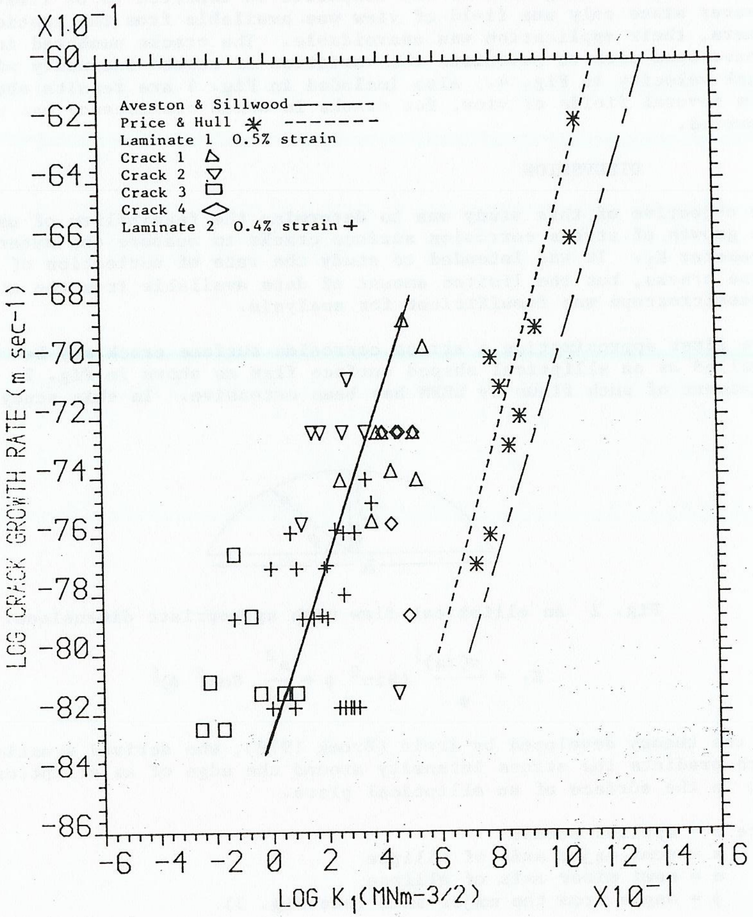

Fig. 4 Crack growth rate/stress intensity data obtained from the elliptical flaw analysis. The symbols represent the analysis for individual cracks, four of which are shown in Fig. 2. The continuous line is a least squares fit to the data. The dotted lines are taken from the work of Price and Hull (1983) and Aveston and Sillwood (1983).

CONCLUSION

The growth of cracks in the surface of GRP under stress corrosion conditions may be analysed by LEFM theory using equations applicable to elliptical surface flaws. Difficulties in the form of interactions between neighbouring cracks can be circumvented by keeping the applied stress low, and so decreasing the crack nucleation rate. At present a programmable photomicroscope is nearing completion which will enable more data to be collected from each specimen. This will not only improve the accuracy of the method but will allow for the factors which affect the initiation of the cracks to be studied.

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