# DETERMINATION AND MODELLING OF THE CRACK GROWTH RESISTANCE OF SiC-FIBRE REINFORCED GLASS CERAMICS

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In this work the toughening behaviour of a number of composite systems was evaluated in terms of the R-curve by performing three-point-bend tests. During testing the initiation and growth of delamination cracks were observed. Based on this observation, a model was developed that describes the crack growth resistance of the materials. The cracks are assumed to be of mixed mode. They initiate in mode II. As the crack grows the mode I-component becomes more important. At large crack lengths, the cracks consist almost entirely of a mode I-component. A comparison of theory and experiment shows that the model offers a reasonable description of the crack growth resistance of the materials.

## INTRODUCTION

Due to their possible use for high temperature applications, much research attention has in recent years been devoted to ceramic matrix composites. These new materials are being developed to increase the toughness of monolithic ceramics and thus provide a greater reliability in structural applications.

With composite materials it can be useful to evaluate toughness in terms of the crack growth resistance curve or the R-curve. Some modelling results that describe the toughening behaviour of ceramic matrix composites are already available. Evans et al (1) and Llorca et al (2, 3) describe the case where a crack grows normal to the fibres in a unidirectional composite material. Ouyang et al (4, 5) use a numerical method to solve this problem. Bordia et al (6), Spearing et al (7) and Charalambides (8) describe the case where delamination cracks grow parallel to the fibres. In both cases the phenomena responsible for the observed R-curve

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behaviour are said to be crack bridging with intact fibres and pull-out of broken fibres. Some of the models mentioned will be described in more detail further on in this paper.

In this work, the toughening behaviour of some ceramic matrix composites is evaluated in terms of the crack growth resistance curve. The R-curves of the available materials are determined and the crack patterns that develop during testing are studied in detail. Based upon these observations a model is developed that describes the crack growth resistance of the materials.

## EXPERIMENTAL PROCEDURE

### Materials

Three different types of materials were tested. All materials were unidirectionally reinforced with Nicalon SiC-fibres. The CAS1- and CAS2-materials both had calcium aluminosilicate-matrices, but were obtained from different suppliers. The BMAS-material had a barium magnesium aluminosilicate-matrix.

### Determination of R-curves

The R-curve of each material is determined using a procedure that is described by Stull and Parvizi-Majidi (9). According to these authors it is necessary to record loading-unloading cycles to be able to determine the R-curve. The specimen has to be loaded just until a pre-cut notch transforms into a crack. Hereafter the specimen has to be unloaded and the crack length measured. This procedure has to be repeated several times. Afterwards, the R-curve of the materials can be determined using the recorded loading-unloading cycles and the measured crack lengths.

### Specimen preparation

The loading-unloading cycles were recorded while performing three-point-bend tests on notched specimens. All materials were available in the form of plates. From these plates samples were machined using a cooled Isomet diamond saw. A diamond saw with a thin (0.5 mm) blade was used to machine a notch in the samples. The orientation in which the samples were tested is schematically indicated in figure 1. The length of the samples was 25 mm, the width 5 mm and the notch-depth to thickness ratio was 0.45.

To be able to follow the crack patterns that developed during three-point-bending one of the side faces of each sample was ground to a surface finish of 15 μm.

### Test equipment

The tests were carried out on a servo hydraulic MTS 810 Material Test System on which a three-point-bending set-up with a span width of 20 mm was mounted. The displacements were measured using the built-in LVDT of the apparatus which had a travel length of 10 mm. The forces were measured using a HBM 1 kN load-cell. The tests were carried out under displacement control with a crosshead velocity of 1 mm/min.

A travelling microscope was used to measure the crack length after each loading-unloading cycle. The microscope also allowed to define the crack pattern that developed during testing.

## RESULTS

All materials showed a very similar behaviour. Four samples were tested for the CAS1- and BMAS-material. For the CAS2-material only two samples were tested. A typical sequence of loading-unloading cycles is represented in figure 2. The resulting points of the R-curve are shown in figure 3 (only the CAS1-material is considered). In each case the crack growth resistance increases with increasing crack length. No plateau value is reached. This is due to the geometry of the samples used : the samples were too small for the crack to advance far enough to obtain a plateau value. The maximum value of the crack growth resistance reached was approximately 40 kJ/m$^2$ in the CAS1-material, 25 kJ/m$^2$ in the CAS2-material and 30 kJ/m$^2$ in the BMAS-material.

In all materials delamination cracks were formed (figure 1) : a crack that initiated at the notch deflected into the fibre/matrix-interface and grew parallel to fibres. SEM-analysis revealed that the phenomenon responsible for the observed toughening behaviour was crack bridging by intact fibres (figure 4).

## MODELLING OF THE CRACK GROWTH RESISTANCE

### Basic models

After the determination of the R-curves of the available materials and the identification of the phenomena responsible for the observed behaviour, a model was developed to describe the crack growth resistance of the materials tested. First some basic models that were used in the further modelling will briefly be discussed.

The model of Evans and McMeeking. Evans and McMeeking model the crack growth resistance of a crack that grows in mode I perpendicular to the fibres. The observed R-curve behaviour is thought to be caused by intact fibres bridging the crack. The influence of the bridging fibres is modelled as a distribution of tension stresses acting on the crack faces. The change in strain energy release rate caused by the bridging can then be written as follows :

$$\Delta G = V_f \int_0^{u_0} \sigma(u) du \tag{1}$$

with u the crack opening, $\sigma$ the stress exerted by the fibres on the crack faces, $u_0$ the crack opening at the end of the bridging zone and $V_f$ the fibre volume fraction.

Based on this formula the crack growth resistance can be calculated if the function $\sigma(u)$ is known.

<u>The model of Spearing and Evans.</u> Spearing and Evans model the crack growth resistance of cracks growing parallel to the fibres (delamination cracks). They assume the crack to grow entirely in mode I. The R-curve behaviour is thought to be caused by misaligned fibres bridging the crack. This type of behaviour has already been described in literature (6, 7, 8). The influence of the bridging fibres is modelled by a distribution of tension stresses acting on the crack faces. Spearing and Evans use the following form for the function $\sigma(u)$ :

$$\sigma(u) = \sigma_0 (1 - \frac{u}{u_0}) \tag{2}$$

with u the crack opening, $u_0$ the crack opening at the end of the bridging zone and $\sigma_0$ the stress acting on the crack faces at u=0.

The following form for the R-curve is obtained :

$$R = G_0 (1 + 2\sqrt{3} (a / h)^2 P^{1/2})^2 \tag{3}$$

with h the thickness of the specimen, b the width of the specimen, a the crack length, $G_0$ the fracture toughness of the matrix in mode I, $P=(\sigma_0{}^2 h/E_{11} G_0)$ and $E_{11}$ the elastic modulus of the composite in the fibre direction.

As the crack opens the bridging fibres are peeled off the matrix. A steady state value is reached when the first bridging fibre is completely peeled off. The crack length $a_{ss}$ at which the steady-state situation is reached is given by :

$$\alpha \left( \frac{h^3 b E_{11}}{12} \right)^{1/4} \tag{4}$$

$\alpha$ is a constant in order to assure that equation (4) is dimensionally correct. In this work $\alpha = 1\ \mathrm{GPa}^{-1/4}$

Modelling of the crack growth resistance of delamination cracks

To model the crack growth resistance of the delamination crack the crack is assumed to be of mixed mode (mode I and mode II). It is assumed that the crack initiates from the notch in mode II and that the mode II-component is dominant at the shorter crack lengths. As the crack grows the mode I-component becomes more important. At large crack length the crack is considered to be almost entirely of mode I. It should be noted that mode I and mode II growth are defined locally at the tip of the delamination crack : the cracks grow entirely parallel to the fibres but under the action of tension stresses the crack grows in mode I and under the action of shear stresses the crack grows in mode II. The observed toughening behaviour is considered to be caused by intact fibres bridging the crack. The bridging is caused by misalignment of the fibres.

The following expression can always be written :

$$R = R_I + R_{II} \tag{5}$$

$R_I$ can be described with the model of Spearing and Evans. This model gives the crack growth resistance $R_1$ of a delamination crack that proceeds entirely in mode I. A weighting factor $a/a_{ss}$ is used to incorporate the assumption that the mode I-component becomes more important as the crack length becomes larger. This leads to the following expression for the crack growth resistance :

$$R_I = G_0 (1 + 2\sqrt{3}(a/h)^2 P^{1/2})^2 \frac{a}{a_{ss}} \tag{6}$$

$R_{II}$ will be modelled analogous to the model of Evans and McMeeking : tension stresses have to be replaced by shear stresses acting on the crack faces and crack opening has to replaced by crack sliding w. This leads to the following expression for the crack growth resistance $R_2$ of a crack that grows entirely in mode II :

$$R_2 = P_0 + V_f \int_0^{w_0} t(w)\,dw \tag{7}$$

with $P_0$ the fracture toughness of the matrix in mode II, $V_f$ the fibre volume fraction, w the crack sliding, $w_0$ the crack sliding at the end of the bridging zone. In this case the fibres are modelled as shear stresses t acting on the crack faces. The shear stresses are assumed to be homogeneously distributed over the bridging zone.

$$t(w) = t \qquad 0 \le w \le w_0 \tag{8}$$

This leads to the following expression for $R_2$ :

$$R_2 = P_0 + V_f t w_0 \tag{9}$$

To obtain the crack growth resistance as a function of crack length a, the function $w_0(a)$ has to be made explicit. Here the following expression is used :

$$w_0 = k\sqrt{a} \tag{10}$$

with k a constant factor.
Here also a weighting factor is used to incorporate the assumption that the mode II-component becomes less important as the crack length increases. This leads to the following expression for $R_{II}$ :

$$R_{II} = (P_0 + kV_f\sqrt{a}t)(1 - \frac{a}{a_{ss}}) \tag{11}$$

By combining equations (5), (6) and (11) the expression for the overall crack growth resistance is found :

$$R = (\sqrt{G_0} + \frac{2\sqrt{3}\sigma_0}{h^{3/2}E_{11}^{\ 1/2}}a^2)^2\frac{a}{a_{ss}} + (P_0 + kV_f\sqrt{a}t)(1 - \frac{a}{a_{ss}}) \tag{12}$$

To apply the model in practice certain material parameters have to be known. Appropriate values for these parameters were taken from literature (10, 11, 12) and are represented in table 1.

| | $E_{11}$ (GPa) | $\tau$ (MPa) |
|---|---|---|
| CAS1 | 144 | 25 |
| CAS2 | 144 | 17 |
| BMAS | 150 | 11 |

Table 1 : Elastic modulus and interfacial sliding stress for the materials tested

For the parameters $G_0$ and $P_0$ a value of 25 J/m$^2$ was assumed. The exact value of these parameters had very little influence on the results. The fibre volume fraction $V_f$ was assumed to be 0.5 for every material. It can be seen that two model parameters are not fixed, namely $\sigma_0$ and t. These two parameters are used in an optimisation procedure : the model equation is fitted to the experimental data. This in turn should yield reasonable values for the parameters. The results of this procedure are shown in figure 3 for the CAS1-material. The values for $\sigma_0$ and t are given in table 2. A comparison of theory and experiment shows that the model offers a reasonable description of the crack growth resistance of the materials. Some deviation still exists. This deviation is random in nature and will probably mainly be due to inaccuracies in the crack length determination.

| | $\sigma_0$ (MPa) | t (MPa) |
|---|---|---|
| CAS1 | 224 | 148 |
| CAS2 | 155 | 19 |
| BMAS | 225 | 170 |

Table 2 : Modelling results for the materials tested

## CONCLUSIONS

It has been possible to determine the R-curves of some ceramic matrix composites by recording loading-unloading cycles in three-point bending. By using a travelling microscope during testing and SEM-analysis after testing the phenomena responsible for the observed R-curve behaviour and the crack patterns could be identified.

For notched materials showing delamination cracks a model was developed that described the crack growth resistance in a fairly accurate manner. The model assumes that the delamination crack is of mixed mode. It initiates in mode II and with increasing crack length the contribution of the mode I-component becomes more important. At large crack lengths the delamination crack consists almost entirely of a mode I-component.

Since two parameters in the model are not fixed an optimisation procedure is carried out. This in turn results in values for those parameters that are quite reasonable. The value for $\sigma_0$ for instance was in all cases only about 10 % of the fibre fracture stress. This is a possible validation for the model. A comparison of theory and experiment showed that the model provided a reasonable description of the crack growth resistance.

It can be concluded that the model contributes to a better understanding of crack growth and toughening of ceramic matrix composites : a delamination crack that grows under three-point-bending initiates in mode II. As the crack proceeds the mode I-component becomes more important. The observed R-curve behaviour is caused by intact bridging fibres that exert tension and shear stresses on the crack faces.

## ACKNOWLEDGMENTS

This research was supported by the Commision of the European Communities as Brite-Euram project BE 4610.

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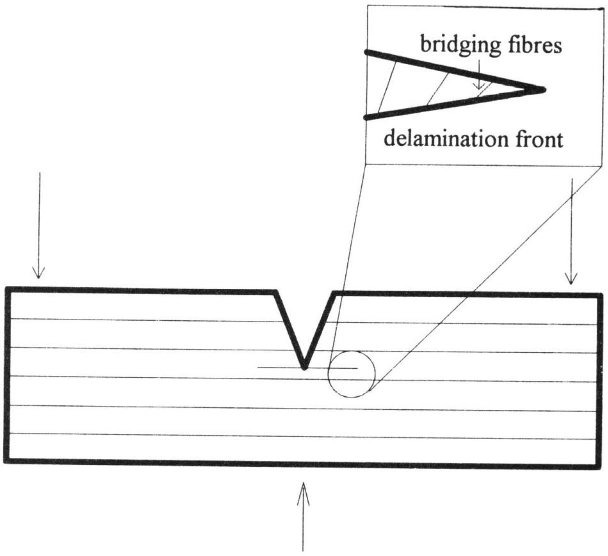

Figure 1 : Orientation of the samples tested and of the delamination cracks observed

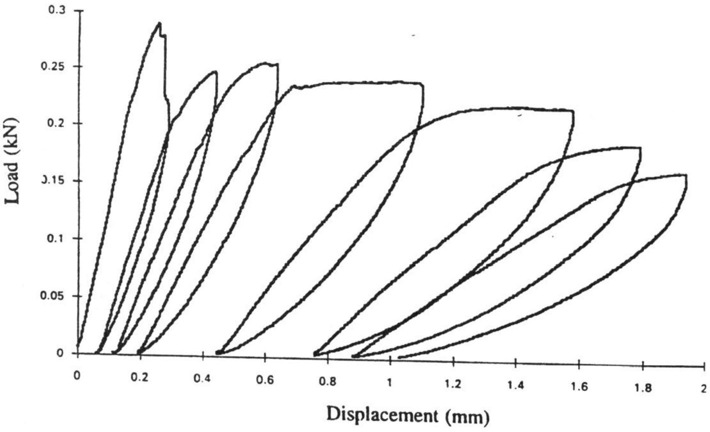

Figure 2 : Loading-unloading cycles for CAS1

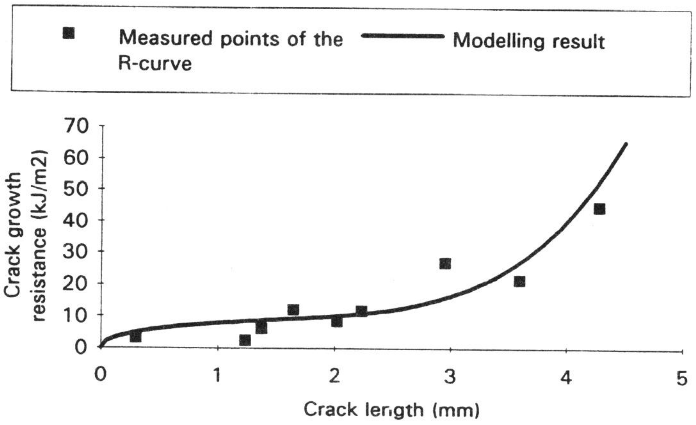

Figure 3 : Measured points of the R-curve and modelling result for CAS1

Figure 4 : Crack bridging by intact fibres