ON THE INFLUENCE OF FIBRE ORIENTATION ON THE DYNAMIC WORK OF FRACTURE OF SHORT-FIBRE REINFORCED THERMOPLASTICS

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The dynamic work of fracture of short-fibre reinforced thermoplastics shows, in general, a nonlinear variation with increasing fibre concentration. To explain such behaviour we assume two reasons: the nonlinearity of the acting energy dissipation mechanisms itself and the change of the dissipation mode due to the change of structural parameters as e. g. fibre orientation.

Taking into consideration the fibre orientation we derive analytical expressions for the dynamic work of fracture for crack propagation perpendicular (T) to the mould fill direction (MFD), which we discuss qualitatively.

INTRODUCTION

A common and approved measure to describe the crack resistance is the work of fracture, the work necessary for driving the crack through the whole sample. It averages the various dissipation energies arising from the separate components and their interactions.

In the paper (1) we have derived expressions for the dissipation energies of composites with fibres of subcritical length, taking into account the number of active fibres within the so-called dissipation zone ahead of the crack tip and the debonding and sliding length of the fibres.

In our calculations we supposed, as a first approximation, that the crack propagates perpendicularly to the direction of fibre alignment. This assumption leads to an overestimation of the work of fracture. This may be caused mainly by the fact that the fibres within the composite are not completely aligned.

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Detailed studies of the microstructure of injection moulded samples of short-fibre reinforced thermoplastics show that there are different fibre orientation zones with respect to the MFD. Their size and the degree of fibre orientation depend on sample thickness and fibre volume fraction.

In this paper we try to provide an improved model for the calculation of work of fracture of short-fibre reinforced composites by taking into account different approximations concerning the fibre orientation.

CONCEPT FOR THE CALCULATION OF WORK OF FRACTURE

Due to the flow characteristics of the melt a certain fibre orientation distribution is induced in injection moulded samples. This fibre distribution has a major influence on the mechanical properties of the composite and thus stimulates a lot of experimental research to specify it (see, for example, Friedrich (2), Fakirov and Fakirov (3)).

Although some studies of the microstructure show (cf. Fischer and Eyerer (4)), that the fibres are spatially oriented within the samples, we rely on the fact that the fibres are mainly lying in the plane of the moulded plaques.

The results of fibre orientation measurements over the whole cross section of the sample can be expressed as the probability density $f(\Theta)$, where Θ denotes the angle between fibre axis and MFD. It has been shown that along the plaque thickness several layers of different fibre orientation can be distinguished. As a reasonable first approximation the real situation can be simplified by assuming three main layers of different orientation - two surface layers (S) and one core layer (K). This leads to the probability densities $f_K(\Theta)$ and $f_S(\Theta)$ for the core and the surface layers (see Fig. 1).

The total fracture work, w_T, is determined by the contributions of the fibres and matrix (w_f, w_m) and the different interaction mechanisms, w_i. Thus we obtain for the specific fracture energy:

$$w_T = w_f + w_m + \sum_i w_i \qquad (1)$$

The terms w_i can be calculated by multiplying the corresponding energy, $W_i(\Theta)$, dissipated at one fibre with the angle Θ, by the specific number, $n_i(\Theta)$, of fibres involved and by subsequent integration over all possible fibre angles:

$$w_i = \int_0^{\pi/2} n_i(\Theta) W_i(\Theta) f(\Theta) d\Theta, \quad \int_0^{\pi/2} f(\Theta) d(\Theta) = 1 \quad ..(2)$$

As derived in reference (1) the density of dissipation centres, n_i, depends on the dissipation zone width, h, which is a function of the composite strength and the debonding strength. To calculate the dissipation energies we use two approximations: (i) separation of the complex loading of a fibre under a certain angle to the applied load, (ii) dissipation energies, $W_i(\Theta)$, are independent of the fibre angle within two main regions $\Theta \lessgtr \Theta_C$. The critical angle Θ_C is defined as that angle where the applied load causes local tension at the fibre/matrix interface high enough for mode I failure.

With these assumptions in mind the interaction energy (eqn (2)) can be expressed as:

$$w_i = w_{i\perp} F + w_{i\parallel} (1 - F), \quad F = \int_0^{\Theta_C} f(\Theta) d\Theta \quad ....(3)$$

with $w_{i\perp} = n_{i\perp} W_{i\parallel}$ and $w_{i\parallel} = n_{i\parallel} W_{i\parallel}$ ($\perp, \parallel$ -crack propagation perpendicular and parallel respectively).

Energy Dissipation for Crack Propagation Perpendicular to the Fibre Axis

This problem was comprehensively discussed in reference (1). For this reason we want summarize only some main results.

We based our model on the following energy dissipation mechanisms (which are illustrated in Fig. 2):
i) debonding at the fibre end and along the fibre/matrix interface (mode II), w_d ; ii) sliding between fibre and matrix along the debonded region, w_s ; iii) fibre pull-out, w_p ; iv) brittle matrix fracture, γ_m .

For the energies of one active element, W_i , we have derived the following expressions:

$$W_{d\perp} =: W_d = 4\pi\, l_d\, \gamma_d^{(II)}$$
$$W_{s\perp} =: W_s = 2\pi\, d\, \tau^{(s)} l_s^2 \Delta\varepsilon \quad ....(4)$$
$$W_{p\perp} =: W_p = \pi\, l^2\, d\, \tau_p / 24$$

where $\gamma_d^{(II)}$ denotes the specific interface debonding energy, l_d and l_s the debonding and sliding lengths (which are functions of the material parameters of the composite and the fibre concentration), τ_p and $\tau^{(s)}$ as the pull-out and sliding shear stress, and $\Delta\varepsilon$ denotes the difference in the ultimate deformation of the matrix, ε_m^F, and the fibres ε_f^F ($\Delta\varepsilon = \varepsilon_m^F - \varepsilon_f^F$), v being the fibre volume fraction, l the fibre length and d the fibre diameter.

Energy Dissipation for Crack Propagation Parallel to the Fibre Axis

For dynamic loading conditions and crack propagation parallel to the fibres, we suppose failure mechanisms as shown in Fig. 3, e. g.:

i) debonding at the fibre/matrix interface (mode I), $w_{d\parallel}$

ii) brittle matrix fracture, γ_m

The debonding energy within the dissipation zone of width $h_{d\parallel}$ we get again by multiplying the debonding energy of one fibre, $W_d^{(I)}$, by the number of debonded interfaces within the crack surface, $n_{d\parallel}$, as $w_{d\parallel} = n_{d\parallel}\, W_d^{(I)}$.

With $\gamma_d^{(I)}$ as the specific debonding energy for mode I loading at the interface the fibre energy is given by

$$W_d^{(I)} = \pi\, d l \gamma_d^{(I)}/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The specific number of debonded fibres within the dissipation zone is obtained by:

$$n_{d\parallel} = \frac{2v}{\pi d^2}\, h_{d\parallel}/2l \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where the factor 1/2 considers the fact that only one surface of two fibres facing one another can be debonded.

On the basis of the stress distribution ahead of the notch tip ($\sigma \sim K/\sqrt{r}$, K - macroscopic stress intensity factor, r - distance from the crack tip) $h_{d\parallel}$ can be estimated by assuming that in a distance of the fibre length, l, in front of the notch tip, the transverse strength of a parallel fibre composite, $\sigma_{c\perp}$, is reached and that at $r = h_{d\parallel}/2$ the tension strength at the fibre/matrix interface, σ_i, is met:

$$h_{d\parallel} \approx 2l(\sigma_{c\perp}/\sigma_i)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

If we use the relations $\sigma_{c\perp} = \sigma_m^F \varphi_m + \sigma_i (1-\varphi_m)$ (φ_m - matrix fracture surface divided by the whole cross section, σ_m^F - matrix strength) we get the width of the dissipation zone:

$$h_{d\parallel} = 2l(1 + \varphi_m(\frac{\sigma_m^F}{\sigma_i} - 1))^2 \quad ......(8)$$

Using eqns (5), (6) and (8) the debonding energy can be approximated by:

$$w_{d\parallel} = v\,\gamma_d^{(I)}\,(1 + \varphi_m(\frac{\sigma_m^F}{\sigma_i} - 1))^2\, l/d \quad ...(9)$$

RESULTS AND DISCUSSION

When knowing the fibre orientation distribution and the relative core width, $\overline{K}$, as published by Friedrich (2), it is possible to calculate the total work of fracture, w_T, for crack propagation perpendicular to the MFD. We compare the following three approximations of fibre orientation:

i) all fibres are parallel to the MFD

$$w_T =: w = (1 - v)\gamma_m + \sum_i w_{i\perp} \quad ......(10)$$

ii) all fibres in the core are perpendicular and all fibres in the surface layers are parallel to the MFD

$$w_T = w(1 - \overline{K}) + w_{\parallel}\overline{K} \quad ....(11)$$

iii) fibre orientation within the three layers

$$w_T = w_T(K)\,\overline{K} + w_T(S)\,(1 - \overline{K}) \quad ....(12)$$

with $w_T(K,S) = w_m(K,S) + \sum_i w_i\,(K,S)$

where $w_i\,(K,S)$ is given by eqn (3), using $F_{K,S}$ instead of F.

Fig. 4 compares the results of w_T provided by the relation (12) and the two approximations (10) and (11).

It becomes evident that the most realistic equation (12) gives the smallest value of work of fracture, whereas the approximations lead to overestimated values. This is mainly caused by the reduced number of fibres perpendicular to the crack direction, when the fibre orientation is taken into account.

The decrease of w for higher fibre volume fractions results mainly from the decrease in the surface layer fraction, $(1-\overline{K})$. These layers contain more fibres parallel to the MFD than the core does. The decrease of their energy contribution cannot be compensated by the increase of the dissipation energy within the core and the increased fibre orientation for higher fibre volume fractions.

The work of fracture depends on the material parameters of the components and those of the interface. Thus, this model allows to assess the influence of different interface properties, as mode I and mode II debonding energy or debonding and pull-out shear stresses. A main improvement, as compared with a parallel fibre model, is given by the fact that mode I processes are involved.

In an analogous way we have calculated the static worf of fracture for different crack propagation directions, see reference (5).

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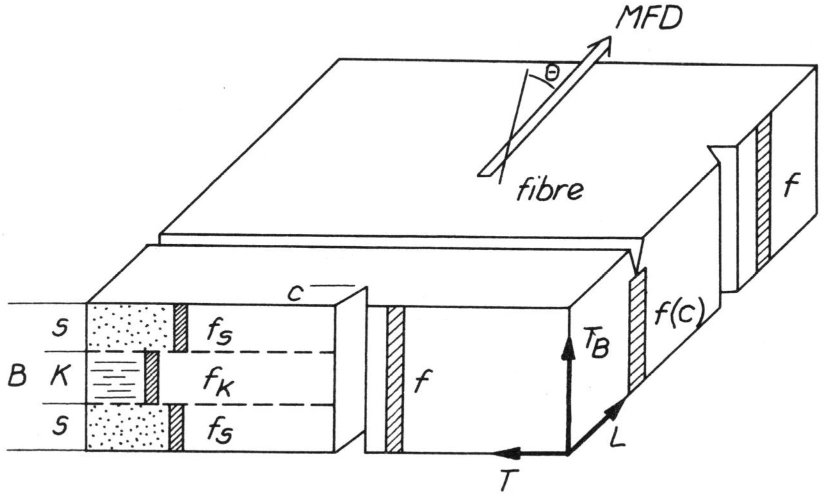

Figure 1 **Geometry of the sample, f - fibre orientation probability denisty, MFD-mould fill direction**

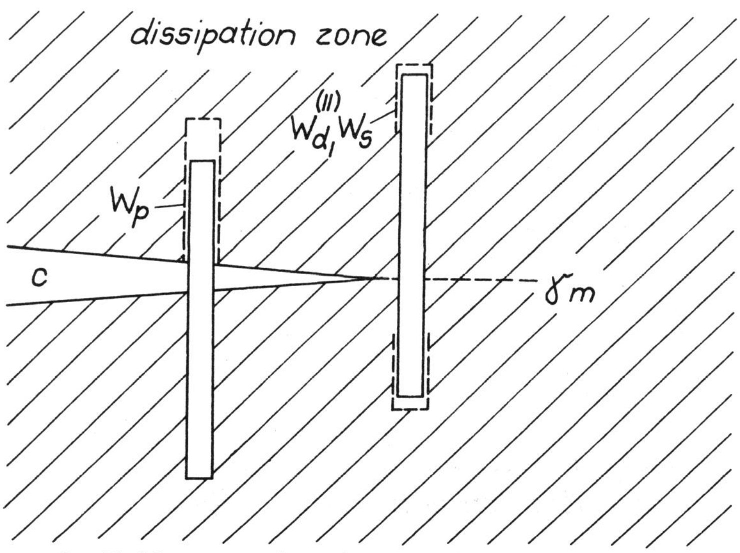

Figure 2 **Failure modes for crack propagation perpendicular to the fibre axis**

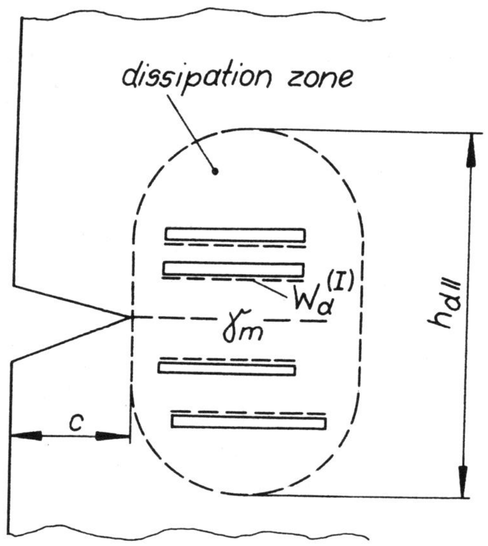

Figure 3 Failure modes for crack propagation along the fibre axis

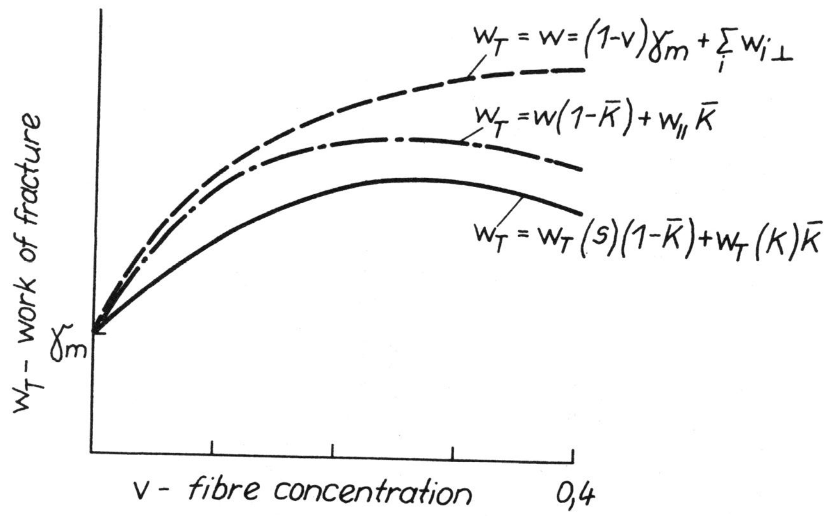

Figure 4 Work of fracture of transverse crack propagation