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Contribution to the problem of tensile and bending-test method for SiC-fibre-reinforced glass

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The Young's moduli of SiC-fibre-reinforced DURAN glass composites with different fibre concentrations obtained from tensile and three-point-bending tests were shown to be in good agreement, while the values of strength and bendover stress and strain were larger in the bending test than in the tensile test. It is assumed that this difference is mainly a consequence of the larger effectively stressed sample volume in the tensile-stress test, compared to the bending test, and it is a consequence of the shift of the neutral line in the bending test towards the compressive-stress region during the fracture process. The second consequence is the reason why the samples behave in a much more ductile way in the bending test and are brittle in the tensile test. The advantages and disadvantages of the two methods are discussed and demonstrated with special regard to the composites mentioned.

1. Introduction

During the development of high-performance materials, fibre reinforcement is of great importance. Since the 1970s, the principle of composites has been applied to glasses, glass ceramics and ceramics [1–4]. The goal of these developments is to use, in particular, the advantageous properties of the components of the composites. In the case of glasses, the low strength, the high brittleness, the low thermal-shock resistance and the large static fatigue are very disadvantageous properties which can not only be removed but can also be turned into excellent properties by fibre reinforcement [5–10].

Concerning the improved mechanical properties, it is very common to test composites or other materials by the bending-test method [5, 6, 7, 11] during the development of new materials, because the experimental handling and sample preparation are very uncomplicated. A disadvantage is that the failure of the samples produced by the superposition of tensile, compressive and shear stresses [12] within the bended sample is not always unequivocal. The maximum stresses appear only in the outer layers of the bending-stressed samples; that is, the effectively stressed sample volume is relatively small compared to the whole volume of the sample and is mainly concentrated in the region of the marginal fibres [13]. The consequence of this is that defects in the interior of the samples remain inactive. The effectively stressed sample volume cannot be enlarged by using larger samples. Also, the difference between the three-point- and four-point-bending-test method is not very large in this respect compared to a pure tensile test [3].

On the other hand the practical performance of tensile-stress experiments is very difficult [14, 15] because large problems arise with the clamping of the samples, which must be free of bending moments and free of slip. The sample itself has to be formed in such a way that fracture really occurs within the sample and not in the neighbourhood of the clamps. The advantage of tensile-stress experiments is the definite stress condition and the larger effectively stressed volume of the samples, which leads to a better statistical result of the experiments.

The tensile-strength values of fibre reinforced glasses and glass ceramics obtained are usually lower by about 60 to 75% than the bending-strength values [15–17]. The origin of this is in the size of the effectively stressed volume.

In this paper, a contribution is given with special respect to SiC-fibre-reinforced DURAN glass. The two different types of testing methods were applied to composite samples of different fibre concentrations; and the properties obtained (Young's modulus, bendover stress, strength and the accompanying strains) are compared and discussed.

2. Experimental procedure

2.1. Preparation of the composite samples

SiC-fibres Nicalon NL202 were used for the reinforcement of DURAN glass. The Young's moduli were about 200 GPa for the fibres and 63 GPa for the glass. The fibre strength was about 2300 MPa and the strain at fracture was 1.4%. The composites were prepared by the sol–gel-slurry method; the steps were as follows: the fibres were drawn through a mixture of glass powder and a Si-alkoxide solution by winding on a drum, hydrolysis and polycondensation of the alkoxide binder, hot-pressing and sawing of the composite

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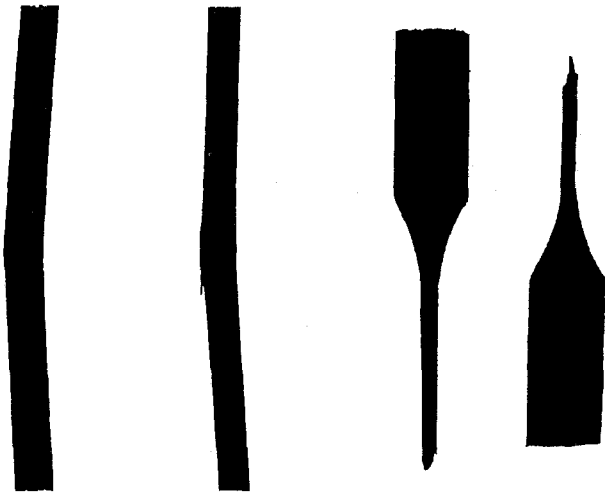

Figure 1 Geometry and typical fracture behaviour of stressed samples in the bending and tensile test.

plates to samples ready for the test measurements. The details are described in [6, 8].

The fibre contents were 40, 45 and 50 ± 2 vol %, which were obtained by variation of the ratio of the glass powder to the alkoxide solution.

The sample dimensions were $95 \times 3 \times 4$ mm^3 for the three-point-bending method; these values were totally unsuitable for the tensile method because the samples were squeezed by the pressure of the clamps or drawn out of them. This latter problem could be solved by preparation of samples with dimensions $95 \times 3 \times 10$ mm^3, which were waist-fitted to a width of 2 mm over a length of 30 mm. The transition from the clamping region to the region of measurement tapered with a radius of 26 mm (see Fig. 1). Within the region of the tensile-test, clamps were used with aluminium gluers which converged conically under an angle of 20 degrees, in order to cause a soft clamping pressure.

2.2. Bending and tensile-test experiments

The two testing methods were performed with a universal testing machine from Zwick in Ulm (type 1455) at a constant loading rate of 10 mm min^{-1}. The strains of the samples were registered by a mechano-electric strain sensor with a sensitivity of ± 0.03%. The bending tests were done in a three-point setup with a span of 75 mm which guaranteed that the ratio, l/d, of span width to sample height was larger than 20 [12, 18]. The clamping device worked on the principle that the clamping pressure increased with increasing tensile stress.

3. Results

Typical stress–strain diagrams of bending and tensile tests for composites with a fibre content of 45 vol % are given in Fig. 2. A so-called mixed-mode fracture occurred under the bending-load condition. After initial failure of the fibres at the tensile-stress side (mode I) the cracks were deflected parallel to the fibres and perpendicular to the acting force (mode II) and the failure continued in a sequential manner starting

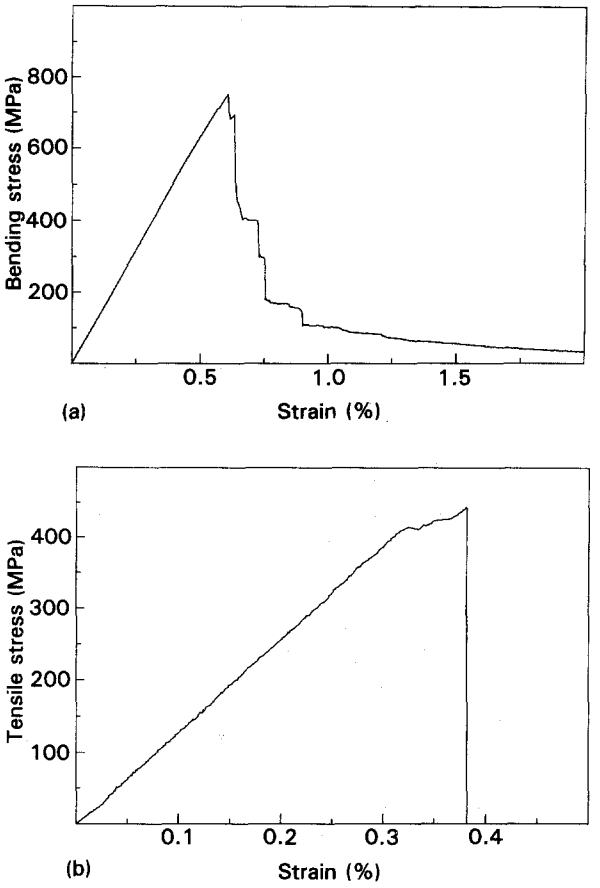

Figure 2 Stress–strain diagrams of SiC-fibre/DURAN glass composites in (a) a bending test, and (b) a tensile test.

successively from the tensile-stress side with respect to the sample height (Fig. 1). The consequence is a stepwise decrease of the remaining stress beyond the strain of the maximum stress (Fig. 2a).

Under tensile stress (Fig. 2b) the samples show brittle fracture after the maximum stress without a stepwise reduction of the stress. Debonding and pull-out, the mechanisms which lead to an increase in the fracture toughness [19], are drastically restricted in the composites of this system (Fig. 1). In a similar behaviour [15, 20] is reported for the fracture of SiC-fibre–ZrO_2 matrix and C-fibre–glass-matrix composites respectively, depending on the type of loading tests.

Fig. 3a represents the dependence of the two fracture-stress test methods as a function of the fibre content. Each point in this and in the following diagrams is the mean value of at least five single measurements, the error bars indicate the standard deviation. A slight maximum of the strength is obtained at a fibre content of about 45 vol % for both tests. With increasing fibre content, the number of fibre–fibre contact points increases leading to a local stress excess and to a reduction of the strength values. From Fig. 3b it follows that the strains at the respective fracture stresses are much more sensitive with respect to the increasing number of fibre–fibre contact points.

The bendover stresses and the accompanying strains also show maxima under the two test methods at a fibre content of 45 vol % (Fig. 4a and b).

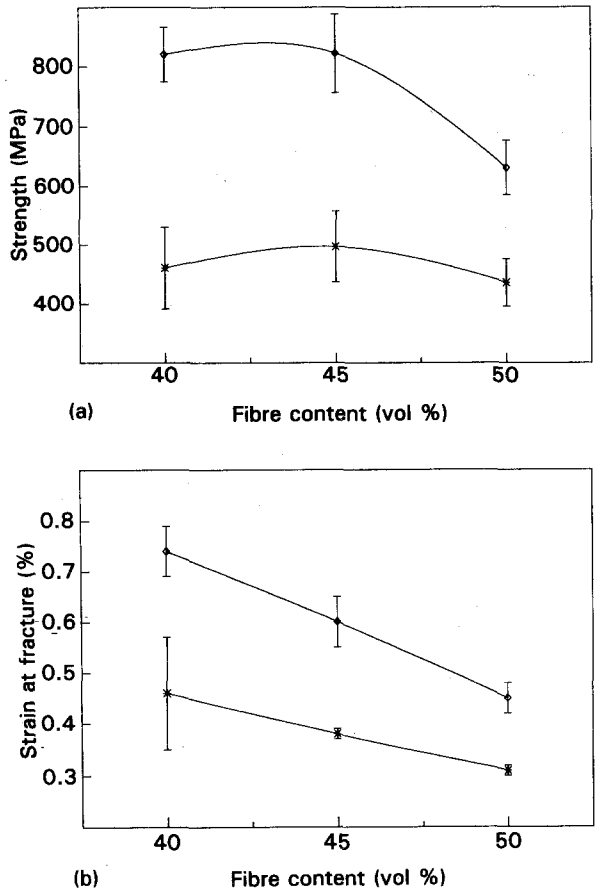

Figure 3 (a) Strengths and (b) strains versus SiC-fibre concentration in (◇) bending and (×) tensile tests.

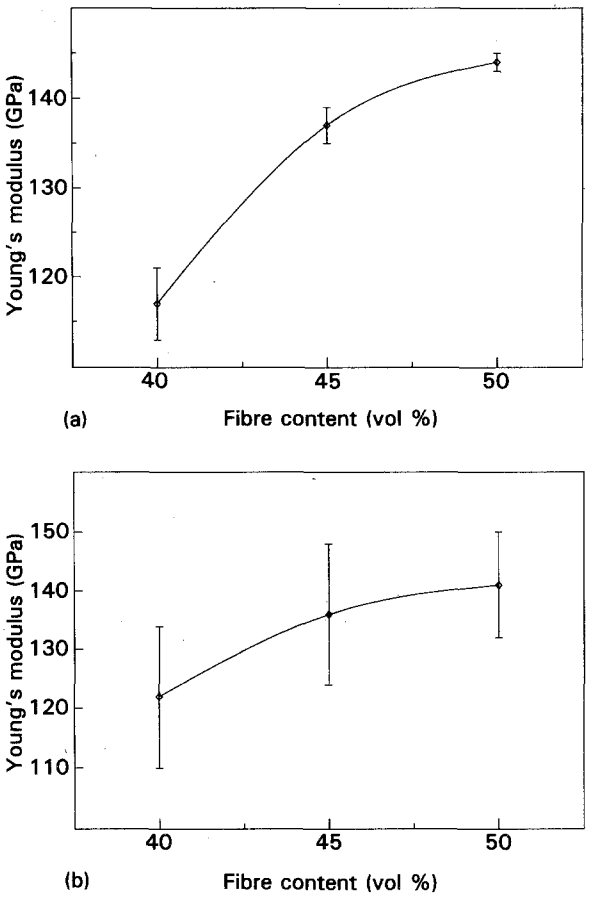

Figure 5 Young's moduli in (a) bending and (b) tensile tests versus SiC-fibre concentration.

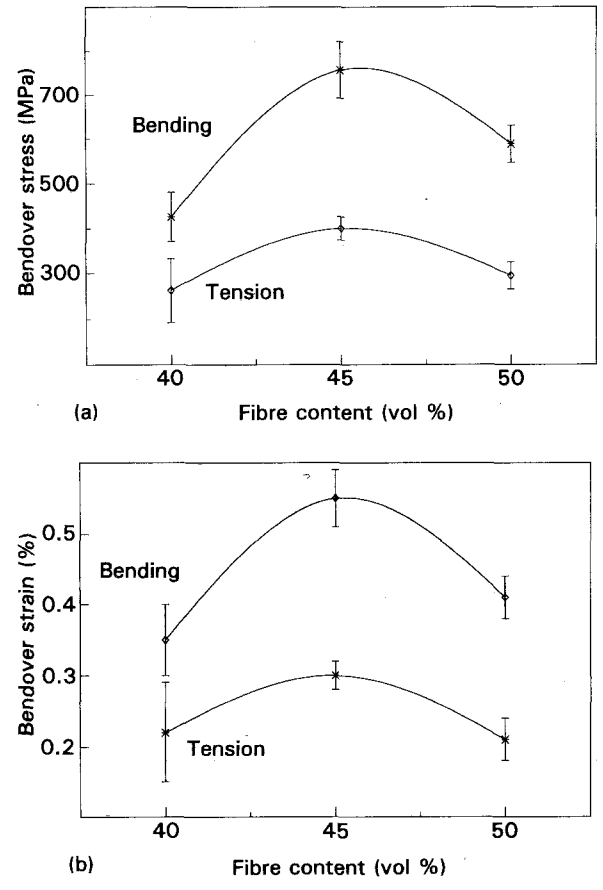

Figure 4 (a) Bendover stresses and (b) strains in bending and tensile tests versus SiC-fibre concentration.

The Young's moduli of the composites increase with fibre concentration and the slope of the curves in Fig. 5a and b is degressive. This means that the incorporation of fibres into the matrix becomes relatively less effective with increasing fibre concentration; that is, the fibre–fibre contact points lead to a decreasing degree of fibre utilization.

4. Discussion

While the Young's moduli of the composites investigated can be regarded as equivalent within the frame of error for the two testing methods (Fig. 5a and b), the values obtained for the maximum stresses (strength) and bendover stresses, as well as the accompanying strains of comparable samples, are distinctly larger in the bending test than in the tensile test.

The ratio of the maximum stress values (strength) of the tensile/bending test and the ratio of the bendover stress of the tensile/bending test are plotted as a function of fibre content in Fig. 6. It is seen that the ratio of the strength values tend to be larger than that of the bendover stress values. This result contradicts the interpretation in [15–17, 21, 22] which report that the shift of the neutral line, produced by microcracks at the tensile side of the specimen above the bendover stress, σ_{bo}, may lead to larger apparent maximum-stress values (strength) in the bending test than the values if no shift of the neutral line takes place. This would lead to a stress ratio, σ(tensile)/σ(bending),

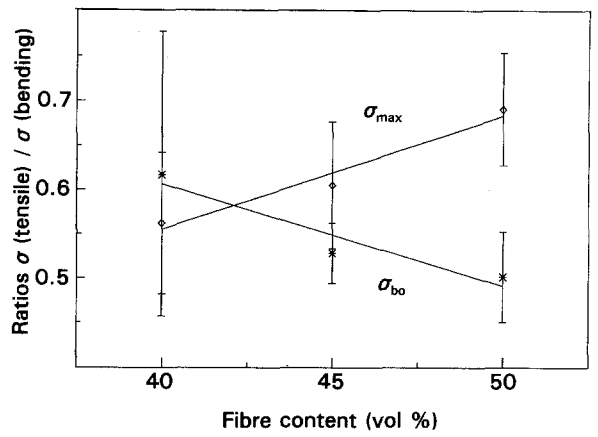

Figure 6 Strength, σ_{max}, and bendover stress, σ_{bo}, as ratios of the results from the tensile/bending tests.

that is larger for the bendover-stress ratio than for the maximum-stress (strength) ratio. In contrast, our measurements show (Fig. 6) that this ratio is lower for the bendover stress, σ_{bo} than for the strength, σ_{max}. The consequence of this is that the shift of the neutral line due to microcracks beyond σ_{bo} is not the dominant cause of the bending stress values being larger than those of the tensile stress. Additionally, the lower ratio for σ_{bo} (tensile/bending) cannot be the result of such a shift at all because the microcracks are much less numerous at the stress σ_{bo} than at σ_{max}.

Another reason for the lower tensile-strength values, compared to those of the bending strength, is the larger effectively stressed sample volume of the tensile test. A relation to estimate the ratio of the tensile strength to bending strength on this basis is given in [16] as follows:

$$\frac{\sigma_{tmax}}{\sigma_{bmax}} = [2(m+1)l_t/l_b]^{-1/m}$$

where l is the acting length of the samples, m is the Weibull modulus of the fibres, the subscript b denotes bending test, and the subscript t denotes tensile test. As a rough approximation, only the acting sample lengths were taken for the ratio because the cross-sections of the samples are identical and the maximum stress in the bending test acts only in the marginal fibres. The Weibull modulus of the Nicalon SiC-fibres was determined in [21] to be $m = 3.3$. With this value, and with an effective sample length of 30 mm for the tensile test and 75 mm (span distance) for the bending test, the ratio of tensile strength to bending strength was 0.69; this corresponds to a tensile strength of 69% of the bending strength, a value which agrees well with the experimental results because the mean value from all the experiments in this investigation of 61% is obtained. This value is in good agreement with the range of 60 to 75% reported in [3, 15, 17, 21, 22].

As was shown in Fig. 2a and b, it is not only the strength values for the two testing methods that are different, the fracture behaviour is also different. While the fracture in the bending test showed a stepwise decrease of the stress and larger strain values, the tensile test showed a brittle fracture behaviour. The different behaviour can again be attributed to the smaller effectively stressed sample volume and its fibres in the bending test and additionally to the successive shift of this region and with it also the successive shift of the neutral line towards the compressive region of the bent sample when cracks are initiated in the manner described above.

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