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The influence of micropores on the dynamic–mechanical properties on reinforced epoxy foams

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The subject of this investigation is the influence of the content of micropores on the mechanical properties of fibre-reinforced epoxy foams. The reinforcement was made of glass or carbon fabrics. A foam-like composite was achieved, which contained 42.0 vol% glass fibres, 27.4 vol% micropores at a density of 1.4 $g\,cm^{-3}$. When the foam was reinforced with 50 vol% carbon fibres the composite contained 15 vol% micropores.

The load increasing test for these reinforced foams showed an interdependence between the damping and the content of micropores; the breaking stress decreased with increasing micropore content.

The Wöhler fatigue test showed similar curves, the fatigue limit decreased with increasing micropore content.

The most distinct influence of micropores on the composite was observed at the impact test. The loss energy increased with increasing content of micropores.

1. Introduction

Fibre-reinforced epoxy resin foams represent a new group of materials, that are now industrially used. The foaming of the matrix material is based on the chemical reaction between the resin and the expanding agent. In this process pores are produced while hydrogen is released. It is a simple, economic and easy to carry out process of foam production.

The production of surfboards may serve as a good example. By using epoxy foams, the production time of standard surfboards was cut in half [4]. One of the first applications of reinforced foams in automobiles was performed in the BMW Z1. A high degree of stiffness and strength has been achieved in the sub frame of the car. Another example is the use of reinforced epoxy foams in the ICE (Inter City Express) railway carriages. There, large sized, non-warping laminates were applied for the lining of the roof and of the windows [1].

2. Materials

2.1. Production of fiber-reinforced epoxy-resin foams

Foaming of epoxy resin is a chemical process. When siloxane is added to the epoxy resin before processing, the application of amino hardeners causes release of hydrogen. The hydrogen acts as expanding agent and the system foams out [4]. The following two reactions occur more or less at the same time [3].

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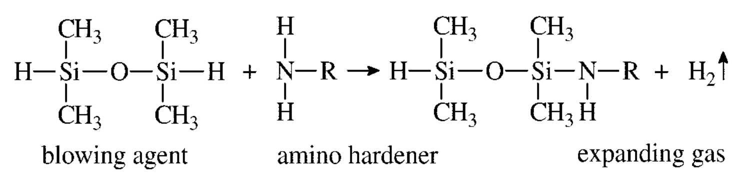

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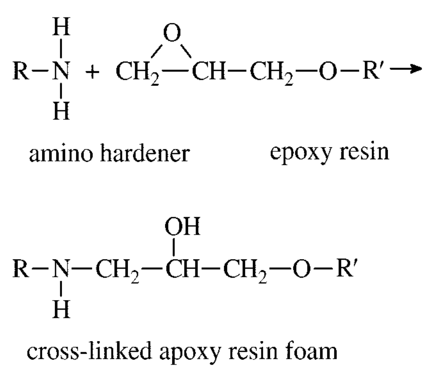

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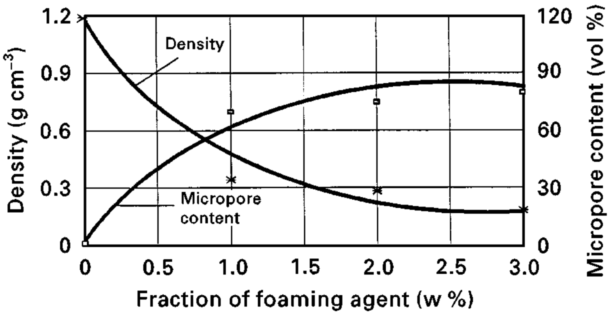

Figure 1 Relationship between density, micropore content and expanding agent for the used resin systems LY 5054/DY 5054/XW 970 R Ciba-Geigy/Germany.

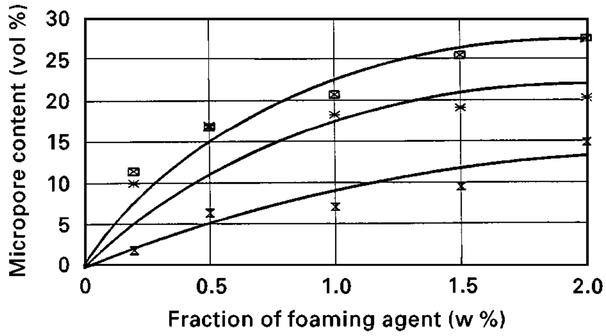

Figure 2 Relationship between expanding agent and micropore content Materials A–C (Table I) with (■) $\varphi_A = 42.5$ vol%; (*) $\varphi_B = 43.3$ vol%; (×) $\varphi_C = 50.0$ vol%.

The amount of expanding agent influences the content of micropores and with this the density of the foam. Fig. 1 shows this relationship for foams without reinforcement. For the production of reinforced foams the epoxy resin system is given into a slightly heated mould. At foaming, a weak expansion pressure is built up. Therefore the permeation among a complex mould and the wetting of the reinforcement is much easier as in epoxy resin laminate production.

2.2. Production of test specimen

For the experiments 4-mm thick laminates were produced in a press between two heated steel plates. The reaction time was approximately 15 min at 80 °C. Polysiloxane was used as expanding agent. To influence the pore content in the matix, the proportion of polysiloxane by weight was varied between 0.2 and 2.0.

The used foam systems were reinforced by different kinds of fibre materials, carbon and glass, and by different kinds of fabrics, woven fabrics (material A, C in Fig. 2) or at-random woven fabrics (material B in Fig. 2).

A significant dependence between reinforcing fibres and micropore content can be observed; this is shown in Fig. 2.

Material A, a foam reinforced with glass fibre fabric, shows the highest content of micropores. This reinforcing material is commonly woven and therefore more dense than the at-random woven fabric of material B. The commonly woven fabric points out to be more of a hindrance for the escaping expanding gas because more pores are developed. The difference between the curves of material A and C might be explained by the higher volume proportion of reinforcement in material A. Table 1 shows the used resin and textile fabrics.

3. Mechanical tests

The laminates used for the mechanical tests were made with the resins and fabrics shown in Table I. Materials with different content of micropores were produced and tested.

3.1. Static load tests

The static experiments (tensile test according to DIN EN 61) show, that by increasing content of micropores, strength is reduced (Fig. 3). But if the tensile strength is normalized by the density, the dependence on the micropore content is almost totally lost.

With increasing micropore content, the Young's modulus, independently of the reinforcing material, remains almost constant. Fig. 4 shows the curves of Young's modulus dependent on the micropore content. A normalization by the density leads to an increase of the Young's modulus with increasing micropore content.

3.2. Dynamic load tests

Since the use of fibre-reinforced composite materials will be increasingly in the field of dynamic loading, knowledge of the dynamic behaviour is very important for the composition of the laminates. First,

TABLE I Used resin and fabrics

Marking	Foam system	Producer		Mixure ratio
	LY 5054 XW 970 R DY 5054			100 : 20 : 0.2–2.0
	Textile fabrics	Ciba Geigy/Germany	Weight of area ($g\,m^{-2}$)	Surface treatment
A	Glass fibre woven typ 21091	Brochier	300	Silane coupling agent TP-binder
B	Glass fibre mat typ U 720	Vetrotex	300	Silane coupling agent polyester binder
C	Carbon fibre woven typ 98150	Interglas	245	Epoxy coupling agent
D	Glass fibre mat typ M 113	Vetrotex	300	Silane coupling agent polyester binder

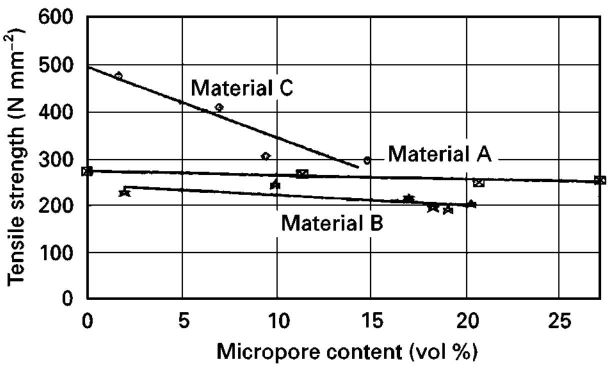

Figure 3 Influence of the micropore content on the tensile-strength of the material A–C with (■) $\varphi_A = 42.5$ vol%; (∗) $\varphi_B = 43.3$ vol%; (◇) $\varphi_C = 50.0$ vol%.

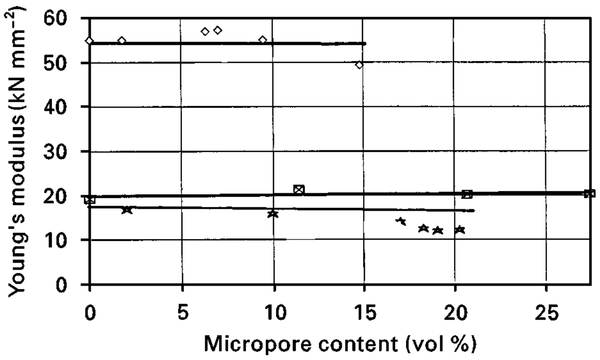

Figure 4 Influence of the micropore content on the Young's modulus of the material A–C with (■) $\varphi_A = 42.5$ vol%; (∗) $\varphi_B = 43.3$ vol%; (◇) $\varphi_C = 50.0$ vol%.

dynamic experiments of fibre-reinforced epoxy-resin foams have shown that the micropores of the laminates can have a positive influence on the mechanical behaviour [2].

Because of the visco-elastic behaviour, a phase shift occurs between applied stress and extension of the material. A sinus-shaped stimulation of the sample, e.g. with a hydropulser, results in a sinus-shaped extension of the sample. The two sinus curves are separated by a phase angle from each other. Overlaying the two measured signals in a tension-extension diagram results in a hysteresis loop. InDyMat (intelligent dynamic material testing), a computer program developed at the Institut für Werkstofftechnik Kassel, records the hysteresis loop at certain intervals (approximately 1000 values each time) and evaluates them. The most used characteristic values of the dynamic test are defined as shown in Fig. 5.

3.2.1. Load increasing test

The load increasing test serves as a quick means to determine the cyclic–dynamic behaviour of the material. The specimens were stretched with a stress ratio of $R = 0.1$ (R = understress/overstress).

In the case of glass-fibre reinforced fabrics, the entire process of damping is independent of the micropore content. As is shown in Fig. 6, the samples fail at similar load levels and number of cycles.

Examination of the dynamic behaviour of carbon fibre fabric (C), and glass fibre mat (B) laminates, in the load increasing test, basically show similar behaviour (Figs 7 and 8), with lower maximum stresses for increasing pore content.

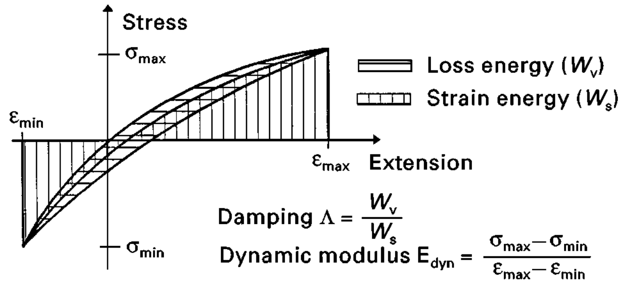

Figure 5 Definition of the characteristic values of the dynamic test.

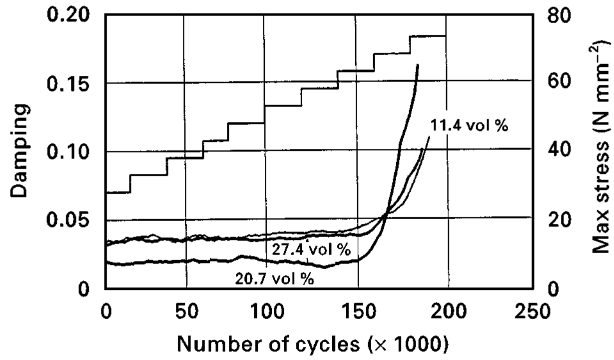

Figure 6 The damping of glass fibre fabric composites depends on the content of micropores $\varphi_A = 42.5$ vol%.

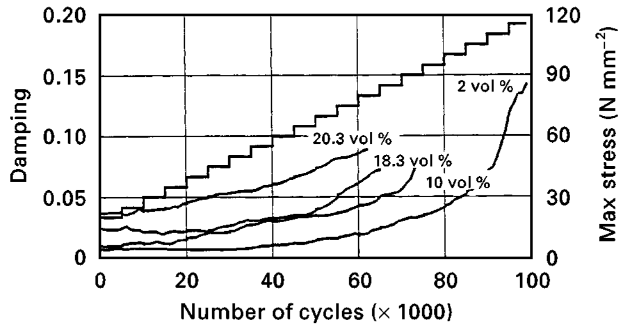

Figure 7 The damping of glass fibre mat composites depends on the content of micropores, $\varphi_B = 30.0$ vol%.

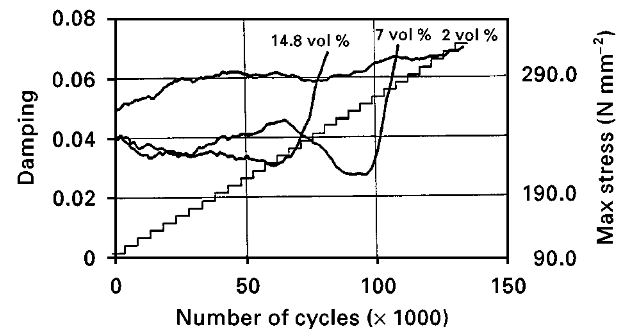

Figure 8 The damping of carbon fibre fabric composites depends on the content of micropores, $\varphi_C = 50.0$ vol%.

The course of the dynamic modulus of the tested carbon fibre composites (C) can be seen in Fig. 9. The dynamic modulus of the foam, reinforced with glass fibre fabric A, is independent of the micropore content.

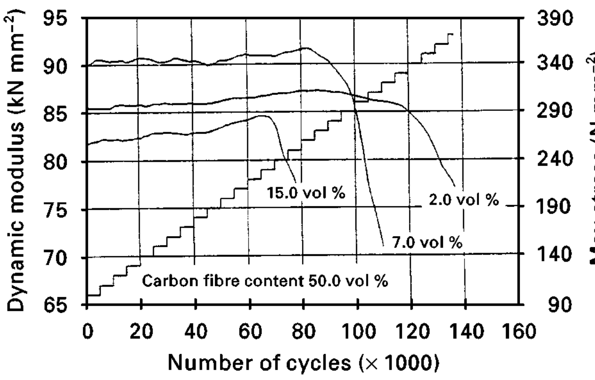

Figure 9 The dynamic modulus of carbon fibre fabric composites depends on the content of micropores $\varphi_C = 50.0$ vol%.

The number of load cycles in which glass mat laminates (B) and carbon fibre laminates (C) failed shifted to lower values.

3.2.2. Wöhler experiments

Material A showed (something that could already be observed during the load increasing test) that the pore content influences the Wöhler curves not much. The Wöhler curves with reference to density are shown in Fig. 10. The laminate with the highest content of micropores (27.4 vol%) shows the best strength properties.

3.3. Impact test

Impact behaviour of the reinforced epoxy foams was measured with a computer program, (Impact). It was developed at the Institut für Werkstofftechnik, Kassel. The force acting on the specimen, is measured in the impactor by a piezo-electric quartz. The deformation is recorded by a PSD (position sensitive detector). Both signals are taken up by the program and the most-used characteristic values are computed. These are defined analogue to the characteristic values of the cyclic dynamic test. The characteristic values of the impact test are defined as is shown in Fig. 11.

Glass mat (D) laminate specimen show similar impact behaviour for different contents of micropores. The stiffness (ascent of the hysteresis loop) decreases with an increasing micropore content (Fig. 12).

Energy loss is neither influenced by the fibre material, nor by the kind of fabric. Fig. 13 shows similar curves for the tested composites.

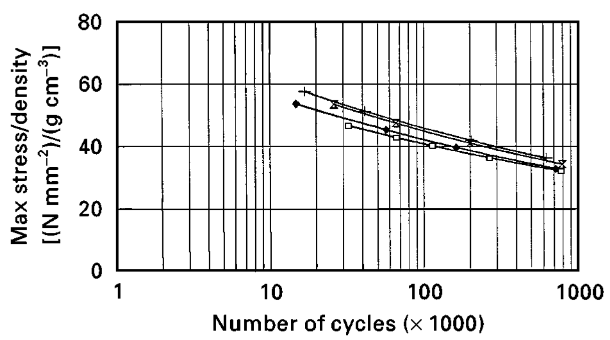

Figure 10 Wöhler curves of the glass fibre fabric composites (A) with different proportions of micropores, $\varphi_A = 42.5$ vol%. Micropore content: (+), 0; (□), 11.4; (◆), 20.7; (☒). 27.4 vol%. $R = 0.1$.

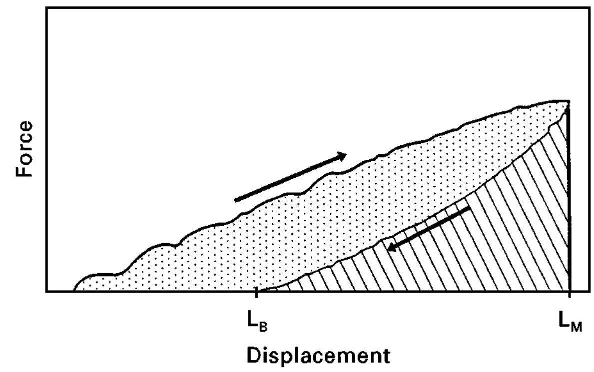

Figure 11 Definition of the characteristic values of the impact test (▦) Loss energy; (■) strain energy. L_B, permanent deformation; L_M, maximum deformation.

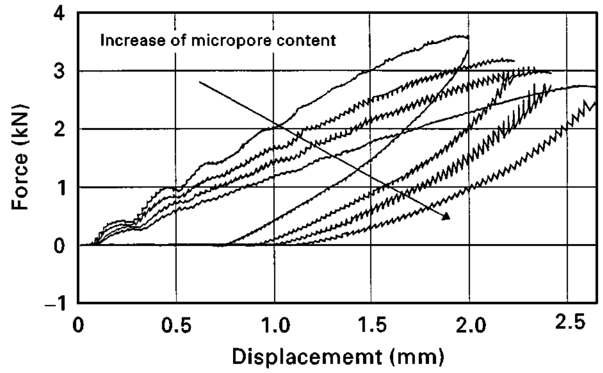

Figure 12 Hysteresis loop for glass mat composites (D) is dependence of the micropore content, $\varphi_D = 21.0$ vol%, impactor mass: 0.75 kg, trail of fall: 0.53 m.

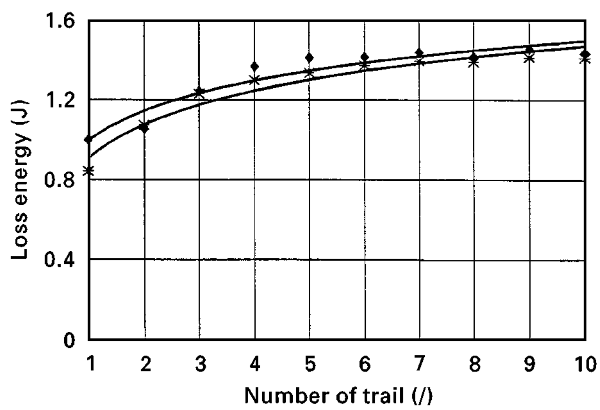

Figure 13 Impact test on materials C (◆) and D (∗). The content of micropores for the materials was C = 27.4 vol%, $D = 26.0$ vol%. $\varphi_C = 32.0$ vol%, $\varphi_D = 26.6$ vol%. Impactor mass: 0.75 kg, trail of fall: 0.4 m.

4. Conclusions

The results, as presented, show that the micropore content of the tested reinforced epoxy foams influences the mechanical properties differently. The static behaviour remains approximately constant. The specific characteristic values, as they increase in Young's modulus, do not depend on the micropore content.

The dynamic properties measured – damping and fatigue limit – do not depend on the micropore content.

The most distinct interdependence between the content of micropores and the characteristic values were observed at the impact tests, where for instance, the loss energy increased with increasing micropore content.

Test data developed by [1] show that an increase of micropore content decreases the thrust strength.

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