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Fibre coating as a means to compensate for poor adhesion in fibre-reinforced materials

Y. TERMONIA
Central Research and Development Experimental Station, E.I. du Pont De Nemours, Inc., Wilmington, Delaware 19898, USA

Using a computer lattice model developed previously, we show that a fibre coating decreases the stress concentration and improves the load carrying capabilities of a broken fibre embedded in a poorly bonded matrix. The optimum fibre coating must have a modulus 1 to 2 times the matrix modulus and a thickness of about 100 nm. Examples are shown in which these fibre coating characteristics can lead to a 400% increase in the load carrying capabilities of a fibre.

1. Introduction

The adhesion between fibres and matrix is one of the key factors determining the mechanical properties of fibre-reinforced composites. All theoretical models, however, assume perfect adhesion and therefore neglect to consider the influence of the boundary layer of the poor bonding developed between fibre and matrix during preparation of the composite. The importance of that so-called "mesophase" layer has been recognized recently [1] and its thickness has been estimated to be in the range 30 to 240 nm.

2. The model

In a recent series of papers [2, 3], we have introduced a computer model for the study of the stress transfer in fibre reinforced composites. In the model, the composite is represented by a regular three-dimensional lattice whose nearest neighbour nodal points are linked by bonds having different elastic constants for the fibre and for the matrix. For a given external strain, these nodes are relaxed towards local mechanical equilibrium with their neighbours by a systematic sequence of fast computer algorithms which steadily reduce the net residual force acting on each node.

The main advantage of the model is that it is microscopic in nature and the approach is applied here to a detailed study of the effects of adhesion and fibre coating on the strength of fibre-reinforced composites. The study is limited to small values of the external strain, for which the deformation is purely elastic. Since in these composites, the fibres are often brittle whereas the matrix is ductile, the present study focuses on the load carrying capabilities of a fibre immediately after it breaks and before the damage has propagated into the surrounding material, i.e. matrix + mesophase layer + coating. That situation is schematically depicted in Fig. 1. The mesophase layer is assumed to be developed entirely on the side of the soft polymeric matrix [1].

We start by describing (Figs 2 to 4) the effects of poor adhesion in the absence of coating. Figure 2 illustrates the shear stress distribution, obtained with the model, for two widely different values of the fibre–matrix adhesion factor. Varying the adhesion in the model was realized by breaking bonds at the fibre–matrix interface, i.e. in the mesophase layer, with probability (1-adhesion factor). The figure is for a ratio of elastic moduli between fibre and matrix $E_f/E_m = 50$, which is in the range of values for a carbon fibre in J2 polymer. The thickness r_{meso} of the mesophase layer was set equal to 9% of the fibre diameter. Since r_{meso} is of the order of 100 nm [1], this corresponds to a fibre diameter d of about 1 μm. The stress concentration factor s is in units of the average tensile stress on the composite. Inspection of the figure shows that, in the case of poor adhesion between fibre and matrix (Fig. 2b), the stress concentration is entirely localized in the mesophase layer which is

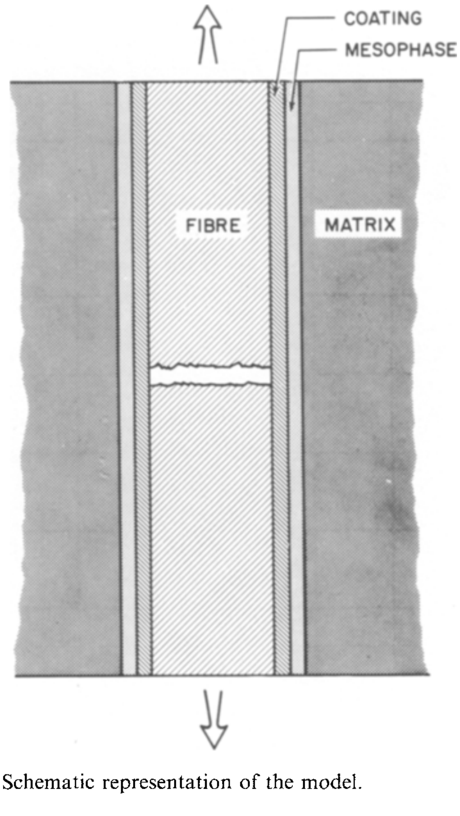

Figure 1 Schematic representation of the model.

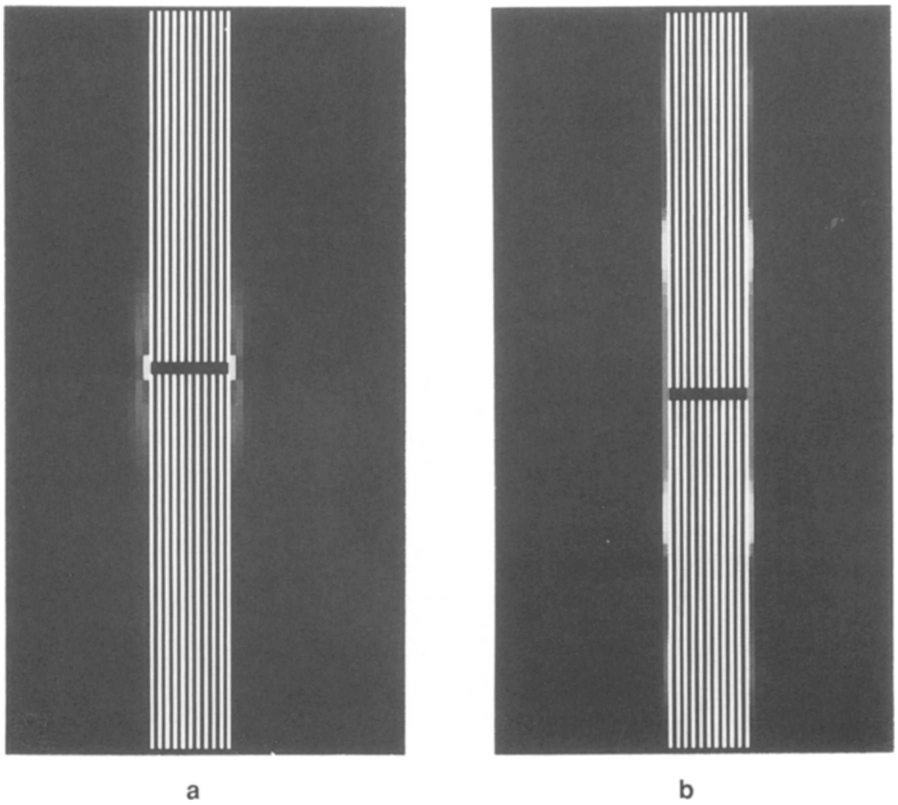

Figure 2 Shear stress distribution, obtained with the model, for two widely different values of the fibre–matrix adhesion factor, (a) 1 and (b) 0.025. No coating was applied to the fibres. The figure is for a ratio of elastic moduli between fibre and matrix $E_f/E_m = 50$, which corresponds to the case of a carbon fibre in J2 polymer. The thickness r_{meso} of the mesophase layer was set equal to 9% of the fibre diameter. The stress concentration factor s is in units of the average tensile stress on the composite.

subjected to large shear deformation (s reaches values as high as 11). In the case of good adhesion, on the other hand, (see Fig. 2a) the shear stress concentration is much lower and more diffuse.

Another deleterious effect of poor adhesion is illustrated in Fig. 3 which shows the dependence on adhesion of the load carried by the broken fibre through shear stress transfer with the matrix. The figure is for a ratio $E_f/E_m = 50$ and for different values of the thickness of the mesophase layer (as percentage of the fibre diameter). The load carried is seen to drop sharply with a decrease in adhesion, that decrease being only weakly dependent on the mesophase thickness. These results are in line with those reported previously [2, 3] on the dramatic increases in fibre critical length with a decrease in fibre–matrix adhesion.

The attainment of good mechanical properties in a fibre-reinforced composite thus definitely calls for an improvement in the fibre–matrix adhesion. That improvement can, however, seldom be realized for a given fibre and matrix. In what follows, we describe how to compensate for the effects of poor adhesion with the help of a fibre coating. We assume that the coating has been chosen so as to give excellent adhesion with the fibre. For the purpose of easy comparison, we also assume that the adhesion between the matrix and the coated fibre is as poor as that with an uncoated one. The thickness and Young's modulus of the coating are denoted by r_{coat} and E_{coat}, respectively. The results are presented in Figs 4 to 6.

Figure 4 depicts the effect of E_{coat} on the largest shear stress in the matrix and in the coating. The bars on the right hand side indicate the largest stress levels measured in the absence of coating. The figure is for different values of the fibre–matrix adhesion factor, assuming $r_{coat} = r_{meso} = 9\%$ of fibre diameter. Inspection of the figure shows that a coating always reduces the stress concentration in the matrix, regardless of the value of E_{coat} and the fibre–matrix adhesion factor. As what concerns the stress concentration in the coating itself, its value increases almost linearly with E_{coat}. Thus, if the strength of the coating is comparable to that of the matrix, E_{coat} should not exceed 2 to 3 times the matrix modulus.

Another consideration of importance when determining the optimum properties of a coating is the load carrying capability of the fibre. Thus, although a very low modulus coating advantageously decreases the stress concentration in both the matrix and the coating (see above), it certainly also decreases the efficiency of stress transfer between the matrix and the fibre. This is exemplified in Fig. 5 which shows the dependence on E_{coat} of the load carried by the fibre, for different values of the fibre–matrix adhesion. The bars on the right hand side indicate the loads carried in the absence of coating. The figure shows that despite a drop in load with a decrease in E_{coat}, a choice $E_{coat} = E_{matrix}$ still leads to a 400% increase in load for an adhesion factor = 0.025. Inspection of Fig. 4 shows that this load increase is also associated with a 36% decrease in the stress concentration.

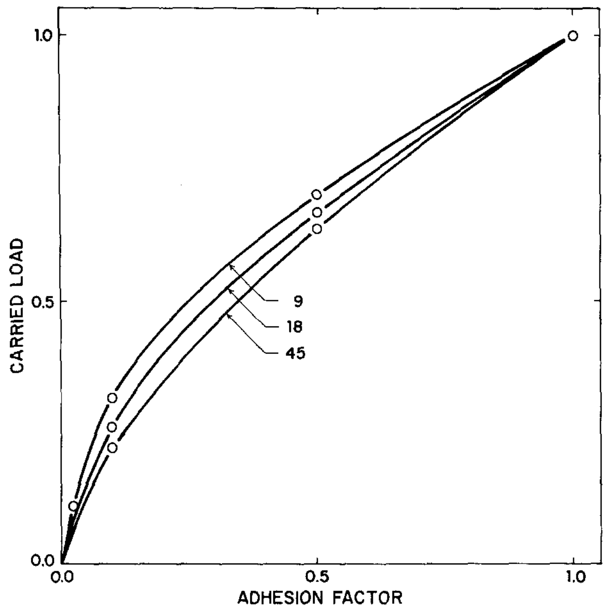

Figure 3 Dependence on adhesion of the load carried by the broken fibre through shear stress transfer with the matrix. The load is in units of its value for perfect adhesion. The figure is for a ratio $E_f/E_m = 50$ and for different values of the thickness of the mesophase layer (as percentage of the fibre diameter). No coating was applied to the fibres.

This points to a very beneficial effect of a fibre coating.

Figure 6 shows the dependence of the results presented above on the ratio between the thickness of the coat and that of the mesophase layer. The figure shows that the coating must be at least as thick as the mesophase layer ($r_{\mathrm{coat}}/r_{\mathrm{meso}} \geqslant 1$) in order to attain optimum performance, i.e. minimum in shear stress and maximum in carried load.

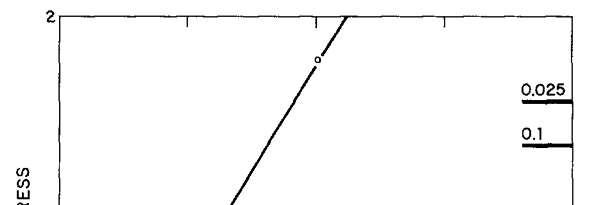

Figure 4 Dependence on E_{coat} of the largest shear stress in the matrix (— —●— —) and in the coating (——○——). The bars on the right hand side indicate the largest stress levels measured in the absence of coating. The figure is for different values of the fibre–matrix adhesion factor, assuming $r_{\mathrm{coat}} = r_{\mathrm{meso}} = 9\%$ of fibre diameter. Stresses are in units of the largest matrix shear stress found in the case of perfect adhesion and no coating. The largest shear stress in the coating was found independent of the adhesion factor.

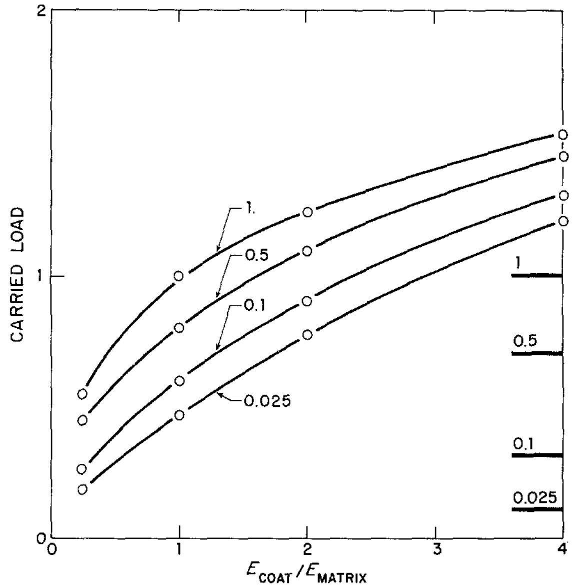

Figure 5 Same as Fig. 4 but for the load carried by the broken fibre.

3. Conclusion

To conclude, the present study clearly indicates that a fibre coating may decrease the stress concentration and improve the load carrying capabilities of a broken fibre embedded in a poorly bonded matrix. The optimum fibre coating must have a modulus 1 to 2 times the matrix modulus and a thickness comparable to that of the mesophase layer, i.e. around 100 nm.

Admittedly, the present study does not represent an exhaustive investigation of the effects of a fibre coating on the mechanical properties of a fibre-reinforced composite. For example, the theory in its present form does not take into account the lateral displacements around the broken fibre due to differences in Poisson's ratio between the fibre, the coating and the matrix. However, the incorporation of these effects into the model would only make the interpretation of our results more difficult. Moreover, it is quite unlikely

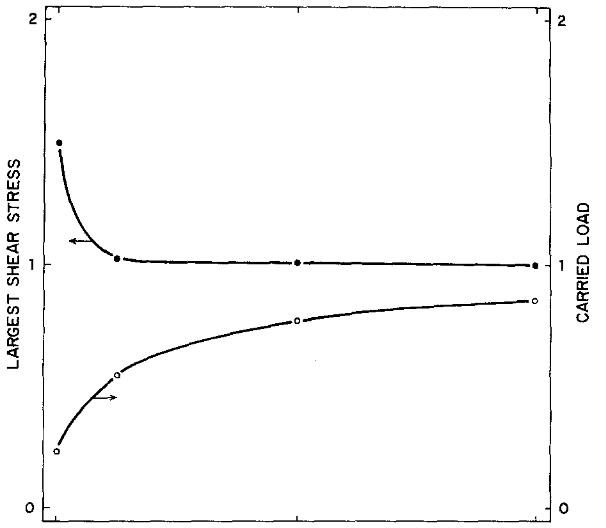

Figure 6 Dependence of the largest shear stress and carried load on the ratio $r_{\mathrm{coat}}/r_{\mathrm{meso}}$ between the thickness of the coating and that of the mesophase layer. The figure is for $E_{\mathrm{coat}}/E_{\mathrm{matrix}} = 1$ and an adhesion factor = 0.1. The thickness of the mesophase layer was kept fixed at 36% of the fibre diameter.

that diffferences in Poisson's ratio would drastically change the conclusions arrived at in the present study (see, for example [4, 5]).

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