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The effect of metal wires on the fracture of a brittle-matrix composite

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The behaviour of stainless steel, work-hardened nickel and annealed nickel wires bridging a crack in a brittle-matrix has been studied as a function of the length and orientation of the wire. The pull-out stress for stainless steel wire in epoxy resin increases less than linearly with wire length, following the behaviour predicted by Takaku and Arridge [6]. Wires inclined at 20° and 40° to the tensile axis gave pull-out stresses some 30% higher than wires parallel to the tensile axis, this increase being attributed mainly to enhanced friction on the bent wire near its point of exit from the matrix. Work-hardened nickel wires fractured when their length exceeded a critical value, and the critical length was significantly shorter for inclined wires than for wires parallel to the tensile axis. In contrast, annealed nickel wires, no matter how long, did not fracture but pulled out at a limiting stress which was slightly higher for inclined wires than for wires parallel to the tensile axis. The results show that, in some cases, there does not exist a critical length above which an embedded wire will fracture rather than pull out of the matrix.

1. Introduction

In brittle-matrix composites the primary function of the reinforcement may be to decrease the susceptibility to brittle fracture. Cement or concrete reinforced with metal wires is an example of a composite of this type which is already in use [1]. The performance of such a composite depends on the interaction of the reinforcing wires with matrix cracks, so as to suppress the propagation of such cracks or to provide some residual strength even when the matrix is completely traversed by a crack. One important aspect of the crack–wire interaction is the force which may be exerted by a wire which bridges a crack in the matrix, acting so as to oppose the opening of the crack. This force may arise from the need to debond the wire from the matrix [2], or to overcome interfacial frictional forces opposing the pull-out of the wires [3], or to deform the wire in some way [4, 5]. The plastic deformation in the bending of a wire which crosses the crack at some angle to the normal to the crack surface has recently been considered in some detail for the case of a weakly-bonded short wire, and it has been shown for example, that the largest crack-bridging force due to plastic bending of the wire occurs for an inclination of the wire to the crack of about 45° [5]. In this paper we study the behaviour of longer or more strongly bonded wires, where the forces due to debonding or interfacial friction are relatively important. Three types of wire were employed: (i) cold-drawn stainless steel wire, having a low elongation to failure (2.4%) and a high strength (UTS = 2040 N mm^{-2}); (ii) work-hardened nickel wire, having a low elongation to failure (~ 2%) and a moderate strength (UTS = 580 N mm^{-2}); (iii) annealed nickel wire, having an elongation to failure of 30%. The matrix was usually an epoxy resin, although some experiments were carried out with a cement matrix.

2. Experimental

Model composites for pull-out tests were made as follows. Two channels, 3 mm wide and deep were machined in a polyester blank which was then divided in two and the two halves separated by a thin mica sheet pierced by two wires which were located in the channels. The matrix material, epoxy resin or cement, was then cast into the channels around the wires. The model then represents a system of two fibres in a matrix which is completely cracked across the section. (The load required to cleave the mica, if there is adhesion between it and the matrix material, is extremely small.) The wires were either aligned with the tensile axis, or inclined symmetrically at ± $\theta°$ to the tensile axis so that the lateral forces arising during pull-out would balance out.

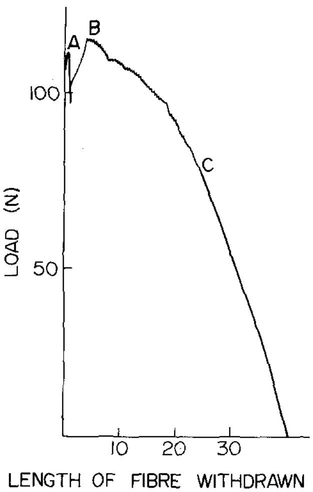

Figure 1 Typical pull-out characteristics of stainless-steel wire in epoxy resin. Debonding occurs at A, the maximum pull-out load at B and from B to C there is a small-amplitude oscillation in the load.

The epoxy resin matrix used was Araldite MY753 with hardener HY956, 100 parts resin to 20 parts hardener. Curing was carried out at room temperature for 24 h followed by 24 h at 70° C. Portland cement paste was used with a water-to-cement ratio of 0.4 and these specimens were stored in water at 50° C for 14 days to harden. The specimens were tested while still wet.

Stainless steel wire of diameter 0.29 mm was used in the cold-drawn condition. (The stainless steel was of the 18/8 type, British Specification BS970 En58A.) Nickel wire* of diameter 0.5 mm, initially in the annealed condition, was hardened by pulling to failure in tension. Annealed wires were prepared by first pulling to failure, to give the same surface condition as the hardened wires, and then annealing either in air or for comparison purposes in argon (no difference in behaviour was found). The annealing treatment was 900° C for 6 min, followed by air-cooling.

Pull-out tests were carried out on an Instron machine at a cross-head speed of 5 mm/min^{-1}.

3. Results and discussion

3.1. Stainless steel wires in epoxy resin

A typical load–extension curve for wire pull-out is shown in Fig. 1. The curve has the same features found by Takaku and Arridge for a similar system [6]. The debonding stress, A in Fig. 1, is taken to be given by the first load drop. It was always of similar magnitude to, although usually somewhat less than, the maximum pull-out stress. The maximum pull-out stress as a function of wire aspect ratio is shown in Fig. 2. The non-linearity of this relationship was explained by Takaku and Arridge by taking into account the reduction in the interfacial frictional force caused by the diametral contraction of the wire under its tensile stress. The expression for the initial pull-out stress, σ_i, derived by Takaku and Arridge [6] is

$$\sigma_i = A\left[1 - \exp - \frac{(Bx_0)}{d}\right] \qquad (1)$$

where A and B are constants, x_0 is the initial embedded length of wire and d the wire diameter. The results for $\theta = 0°$ (Fig. 2) are well fitted by Equation 1 with $A = 1810\,\mathrm{N\,mm^{-2}}$, and $B = 1.18 \times 10^{-2}$. The constant A represents the limiting pull-out stress for very long wires and since its value in this case is below the tensile strength of the wire, the implication is that the stainless steel wire cannot be fractured at $\theta = 0°$, no matter how large its aspect ratio is. The pull-out stress for inclined wires follows the same form of relationship to aspect ratio but at a significantly higher stress level (Fig. 2). Extrapolation indicates that fracture of inclined wires would occur at lengths much longer than those it was practicable to test. The increase in stress is much larger than can be accounted for by the direct contribution of plastic bending, which could add only about 100 N mm^{-2} at most to the pull-out stress [5]. The magnitude of the increase can be accounted for by the action of frictional forces on the wires as it turns through an angle near the point of its exit from the matrix. We may assume that this increases the tensile stress, σ, in the wire above its value σ_0 approaching the turn, in the same manner as the tension in a rope wrapped around a drum is increased, that is

$$\sigma = \sigma_0 \exp \mu\theta \qquad (2)$$

where μ is the coefficient of friction and θ the angle turned through. With $\mu = 0.5$ [6] and $\theta =$

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* The nickel wire was commercially pure as supplied by British Driver–Harris Co Ltd.

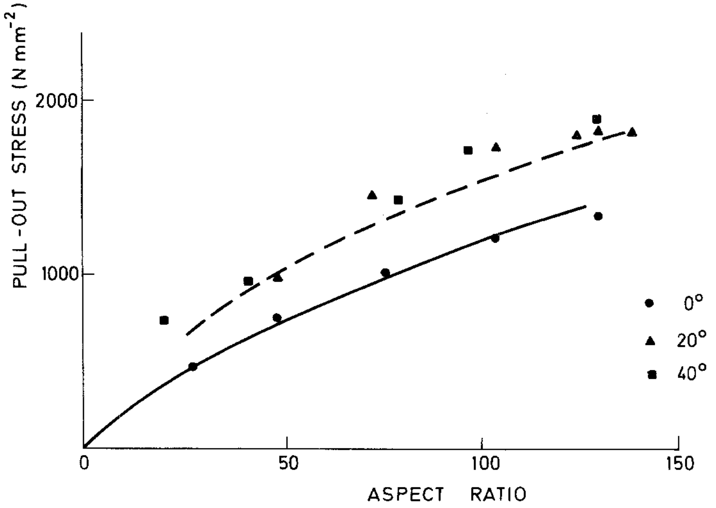

Figure 2 The effect of aspect ratio on the pull-out stress for steel wire embedded in epoxy resin. The full line through the 0° points is the Takaku and Arridge approximation and the broken line is an estimate for the 20° fibre.

0.3 radius, this gives a 16% increase in the pull-out stress. When this increase together with a contribution of 100 N mm^{-2} due to plastic bending is added to the results for $\theta = 0°$, as shown in Fig. 2, the resultant pull-out stress is fairly close to, although still slightly less than, that observed at $\theta = 20°$.

The observation that the pull-out stress for $\theta = 40°$ differs little from that at $\theta = 20°$ can be explained by the fact that the angle actually turned through at $\theta = 40°$ differs little from that turned through at $\theta = 20°$ due to more extensive deformation of the matrix by the wire at $\theta = 40°$.

3.2. Work-hardened nickel wire in epoxy resin

The tensile strength of the hardened nickel, 580 N mm^{-2} is much less than that of the stainless steel and this together with a small elongation to failure leads to the failure of the wire, instead of pull-out, above a critical aspect ratio (Fig. 3).

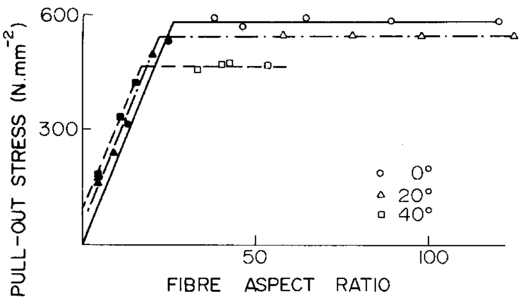

Figure 3 The variation of the pull-out stress with aspect ratio for hardened nickel wire in an epoxy resin matrix. The open symbols denote fibre fracture rather than pull-out.

The relationship between pull-out stress and fibre aspect ratio is interrupted by wire failure before the non-linearity predicted by Equation 1 becomes evident. In other words, it is a sufficiently good approximation to treat the pull-out process at $\theta = 0°$ as being opposed by a constant interfacial shear stress τ, within the range where pull-out rather than fracture is observed.

Fig. 3 shows that the inclination of the wire has a marked effect on the results. The failure stress is reduced by fibre inclination, due to the combination of direct tensile and bending stresses induced in pull-out. Observations of the fracture surfaces showed that failure initiated at the convex side of the bend in the fibre, at the position of maximum curvature a little way inside the matrix. Aveston *et al.* [7] have commented on the reduction in failure stress of a fibre subjected to a combination of tensile and bending stress during pull-out for the case of an elastic fibre, and Piggott [8] has also proposed an expression for the dependence of fracture stress on fibre orientation for a brittle fibre. In our case the behaviour of the fibre is plastic rather than elastic and we are not able to account theoretically for the magnitude of the observed reduction in failure stress with increasing inclination. The important effect of this reduction is that it leads to a reduction in the critical length of wire with increasing fibre inclination. The increase in the magnitude of the pull-out stress with increasing wire inclination also makes a significant, although smaller, contribution to the reduction in critical length (Fig. 3). The reduction in critical length is very marked, for example, it is reduced from 25 fibre diameters at $\theta = 0°$ to 16 fibre diameters at $\theta = 40°$. The largest possible work of fracture due to pull-out in an aligned composite where the fibre is acted on by a constant interfacial shear stress is given by [3]

$$W_{\max} = \frac{V_f \sigma_u l_c}{12}, \tag{3}$$

where V_f is the volume fraction of fibre, σ_u the failure stress of the fibre and l_c its critical length. Our results show that the effect of introducing variations in fibre orientation will be to reduce l_c and hence reduce the maximum possible work of pull-out.

3.3. *Annealed nickel wire in epoxy resin*

The case where the wire has a relatively low yield stress and substantial ductility gives the most complex and interesting behaviour. The most striking observation is that debonding and pull-out always occurred, even for lengths of wire as great as five times the critical length for the work-hardened nickel wire [9]. Fig. 4 shows a typical load-extension curve for wire pull-out and Fig. 5 shows the dependence of the maximum pull-out stress on the aspect ratio of the wire. For $\theta = 0°$ a limiting pull-out stress of 350 N mm^{-2} is observed. This is equal to the flow stress in a tensile test of the annealed nickel wire at a plastic strain of approximately 5%. The behaviour for wires inclined at $\theta = 20°$ and 40° was essentially similar, with a slightly higher limiting pull-out stress, reached at a somewhat lower fibre aspect ratio (Fig. 5).

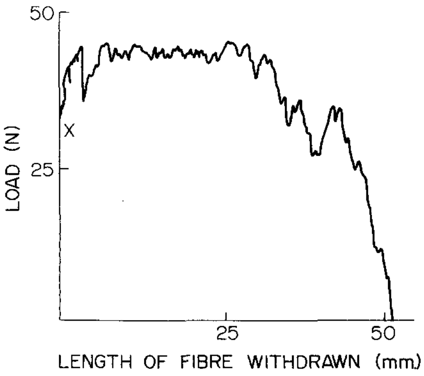

Figure 4 Pull-out characteristics of annealed nickel wire embedded in epoxy resin.

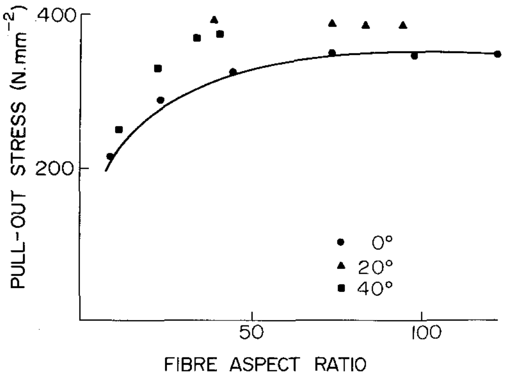

Figure 5 The effect of aspect ratio on the pull-out stress of annealed nickel wires in epoxy resin.

We will now discuss whether the value of the limiting pull-out stress for annealed nickel wires can be accounted for by a generalization of the theory of Takaku and Arridge to cover the effect of the diametral contraction of the wire accompanying plastic as well as elastic tensile strain. It is assumed that the matrix behaves elastically with Young's modulus E_m and Poisson's ratio ν_m. Then by treating the fibre and matrix as concentric cylinders with very large outer radius, the normal stress at the interface is related to the matrix displacement u at the interface by

$$\sigma = \frac{E_m}{1+\nu_m} \cdot \frac{2u}{d} \tag{4}$$

where d is the inner diameter of the matrix cylinder. The frictional shear stress is assumed to be related to the normal stress by

$$\tau = \mu(\sigma + \sigma_0), \tag{5}$$

then from Equation 4

$$\tau = \mu(\sigma_0 + K\Delta d/d_0) \tag{6}$$

where σ_0 is the initial normal stress acting on the interface (due to matrix shrinkage), $K = E_m (1 + \nu_m)$ and $\Delta d/d_0$ is the nominal diametral strain of the wire. When the fibre is elastic, the diametral strain is related to the longitudinal strain, e_f, by Poisson's ratio. In our case, let the ratio of the diametral to longitudinal strain be $-\phi$, the value of which depends on the degree of fibre plasticity. Now the force p_f in an element of fibre of diameter d is related to the interfacial shear stress τ by

$$\frac{\mathrm{d}p_f}{\mathrm{d}x} = \pi d\tau \tag{7}$$

where x is the distance of the element from the fibre end. The nominal diametral strain $\Delta d/d$ and nominal fibre stress σ_f may be substituted into Equation 7 to give

$$d\sigma_f/dx = \frac{4\tau}{d_0}\left(1 + \frac{\Delta d}{d_0}\right); \qquad (8)$$

from Equation 6

$$d\sigma_f/dx = \frac{4\mu}{d_0}(1 - \phi e_f)(\sigma_0 - K\phi e_f). \qquad (9)$$

From the tensile stress–strain curve, the relation between e_f and σ_f is known, and hence Equation 9 may, in principle, be solved to give the variation in fibre stress along the fibre length. The limiting pull-out stress may be obtained more simply from the consideration that it occurs when $d\sigma_f/dx = 0$. On moving from the embedded end of the wire, σ_f increases and τ decreases until the point is reached where the interfacial normal stress and hence τ is reduced to zero. At this point $d\sigma_f/dx = 0$ and no further increase in σ_f is possible. The limiting pull-out stress is, therefore, that at which

$$e_f = \frac{\sigma_0}{K\phi}. \qquad (10)$$

Typically shrinkage stresses in resins are on the order of 10 N mm^{-2} [10]. Setting $\sigma_0 = 10\,\text{N mm}^{-2}$, $K = 2000\,\text{N mm}^{-2}$ and $\phi = 0.5$ gives $e_f = 1\%$, so that from the stress–strain curve for annealed nickel wire a limiting stress of approximately 200 N mm^{-2} is predicted. This is considerably below the observed limiting stress of 350 N mm^{-2}. In terms of strain the discrepancy is even more marked, the stress of 350 N mm^{-2} corresponding to a tensile strain of 5% compared to the predicted value of 1%.

The explanation for the high pull-out stress observed may lie in the roughness of the wire surface. In order to obtain a similar surface to the work-hardened wire, the annealed wire was pulled to fracture before being annealed, and this introduced considerable irregularity in the wire diameter. Talysurf measurements showed a diametral variation of as much as 4% after pulling and annealing as compared to 0.1% in the wire as-received. In pulling the wire from the matrix, the wire and/or the matrix must deform in order to overcome the mechanical keying of the surfaces produced by this roughness. It is suggested that this, rather than the overcoming of Coulombic friction, determines the maximum pull-out stress. However, for a sufficiently smooth wire, the generalized Takaku and Arridge theory described above may be valid.

3.4. Nickel wire, in cement

The behaviour of annealed and work-hardened nickel wires in a cement matrix were compared for $\theta = 0°$. As reported elsewhere [9], the behaviour in the cement matrix was closely similar to that in the resin matrix. For the work-hardened wire the critical length was 28 fibre diameters, compared to 25 fibre diameters in resin and for the annealed wire the limiting pull-out stress was 320 N mm^{-2} in cement compared to 350 N mm^{-2} in resin.

4. Conclusions

(1) For the pull-out of stainless steel wire from epoxy resin at $\theta = 0°$ our results are in agreement with those of Takaku and Arridge. Inclined wires ($\theta = 20°$ or $40°$) show a higher pull-out stress.

(2) For work-hardened nickel wires in epoxy there is a transition from pull-out to fracture at a critical wire length, which decreases markedly as the angle of inclination of the wire increases.

(3) Annealed nickel wires in epoxy show no transition from pull-out to fracture, i.e. there is no critical length. The limiting pull-out stress was larger than could be accounted for by considering the reduction in Coulombic friction due to diametral plastic contraction of the wire. This was attributed to a mechanical keying effect due to surface roughness of the wire. Inclination of the wire has only a small effect, in slightly raising the limiting pull-out stress.

(4) The behaviour of nickel wires in cement was closely similar to that in epoxy resin, at $\theta = 0$, suggesting that resin matrix composites may in some respects at least be suitable models for cement–matrix composites.

(5) The general implication of these results for the work of fracture due to pull-out of composites containing metal wires is that, provided wires of too limited strength or ductility are avoided, the work of fracture may far exceed that calculated to be a maximum on the assumption of a constant interfacial shear stress which leads to a critical fibre length. Inclined wires in general show slightly higher pull-out stresses than those at $\theta = 0°$, but this will not usually be sufficient to introduce a critical length for inclined wires. High works of fracture due to pull-out will, therefore, be possible in composites containing

randomly oriented wires as well as in aligned composites.

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