The Effect of Fibre Diameter on the Strength of Composite Materials

The ultimate tensile strength of a composite material obeys the rule of mixtures, as given by

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad (1)$$

where σ_c is the composite ultimate tensile strength, σ_m is the matrix ultimate tensile strength, σ_f is the fibre ultimate tensile strength, V_m is the volume fraction of the matrix, and V_f is the volume fraction of the fibre. This relationship has been verified experimentally by McDanels *et al* [1] for composites having a copper matrix and tungsten fibres, and by Piehler [2] for composites having a silver matrix and steel fibres. According to equation 1, the diameter of the fibres should have no effect on the ultimate tensile strength of a composite material, although the strengths of whiskers and single filaments have been shown to be size-dependent [3, 4]. In order to see whether or not the size of the fibres does actually affect the strength of a composite material, we have performed experiments in which the fibre diameter was varied from 10^{-1} to 10^{-5} mm, in a series of steel in copper composite materials.

The composite materials were made from phosphorous-deoxidised copper tubing and Weldco 2001 Swedish steel welding rod. The welding rod was first drawn to 1.41 mm outside diameter. Then it was placed inside a piece of small copper tubing (3.18 mm outside diameter, and 1.65 mm inside diameter). Next, twelve pieces of the small copper tubing, each containing a steel rod, were placed inside a piece of large copper tubing (15.9 mm outside diameter, and 13.8 mm inside diameter). Finally, the whole assembly (the composite) was sintered in a nitrogen atmosphere at a temperature of 1064° C. The sintering assured good contact between the parts, prior to the swaging operation which followed.

The following procedure was repeated to produce the composite materials shown in table I. (*a*) The composite was swaged from 15.9 mm outside diameter to 7.37 mm outside diameter and sintered. (*b*) It was then drawn to an outside diameter of approximately 1.59 mm. Tensile tests were performed on this material after it had been annealed at 815° C for 1 h and furnace-cooled. (*c*) After annealing, fifty pieces of the composite were placed inside a piece of large copper tubing and sintered. These steps were repeated until the steel fibres had a diameter of approximately 10^{-5} mm. The above procedure is similar to that used by Levi [5] and by Cline *et al* [6] in their studies on magnetisation.

Tensile stress versus strain data were obtained using a TTCM Instron Tester with a CM-FR load cell. All tests were made at an elongation rate of 0.5 cm/min.

Data from the stress-strain curves for the starting materials agreed with existing values in the literature [7]. We found σ_m equal to 30800 psi (21.2×10^7 newton metre^{-2}) and σ_f equal to 40100 psi (27.6×10^7 newton metre^{-2}). The elongation at fracture was 37% for copper, and 42% for steel. This is unusual. In most composite materials, the fibres are less ductile than the matrix. However, in our study, the fibre material is both stronger and more ductile than the matrix material.

Fig. 1 is a graph of our measured values of the ultimate tensile strengths for the composites, σ_c, versus the fibre volume fraction, V_f. Since the composites have a maximum of 14% steel, according to the rule of mixtures the composite ultimate tensile strength should be close to the ultimate tensile strngth for copper. However, some of our measured composite ultimate tensile

TABLE I Composite dimensions

Calculated fibre diameter d_f mm	Number of fibres per cross-section	Fibre cross sectional area / Total cross sectional area $= V_f$ (%)	Outside diameter of, composite rod mm
1.78×10^{-1}	12	13.9	1.6
2.08×10^{-2}	600	9.6	1.6
2.44×10^{-3}	30000	6.6	1.6
2.87×10^{-4}	1.5×10^{6}	4.6	1.6
3.35×10^{-5}	75.0×10^{6}	3.2	1.6

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strengths exceed the ultimate tensile strength for steel.

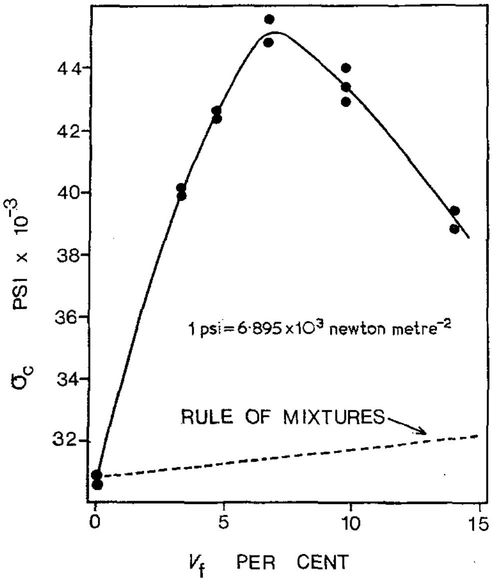

Figure 1

It should be noted, from table I, that each point in fig. 1 represents a different d_f as well as a different V_f. Furthermore, the data of fig. 1 show that, after the changing fibre volume fraction has been accounted for, the composite strength increases as the fibre diameter decreases. The increase in composite strength can be related to σ_f. We assume that the experimental value of σ_f which was determined from bulk samples of steel (1.6 mm diameter), is not applicable to the much thinner fibres. Instead σ_f is calculated from the rule of mixtures, using experimental values for all the other terms. The resulting σ_f is shown in fig. 2.

The increase in σ_f could have several contributory causes. Smaller diameter fibres presumably are intrinsically stronger, as is implied by fig. 2. The greater number of fibres per unit cross-sectional area, which are present at smaller d_f (see table I), could also affect the strength, by impeding the propagation of dislocations in the matrix. Also, it is possible that the strength would be affected if any α or γ phase material was present at the steel-copper interface.

Whatever the mechanism, with large enough V_f and small enough d_f, it is possible to produce composite materials which have ultimate tensile strengths higher than either of the starting materials. Furthermore, it has been shown that if the rule of mixtures is applicable, the diameter of the fibres does affect the strength of a composite material.

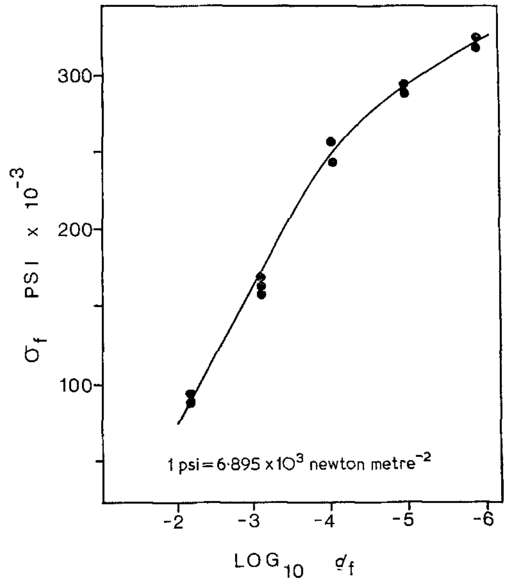

Figure 2

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