ciency, measured metabolic energy gives a much closer indication of the behavioural and ecological costs of flight than can aerodynamic models. Because similar flat power–speed curves have been found in some birds[1] (although not in bats) it is advisable to avoid making incautious use of theoretical estimates of flight costs: the approach[2] of assuming a constant efficiency independent of speed and size cannot at present be justified. Reconciliation of physiological and aerodynamic approaches to energetics, and in particular the deeper understanding of efficiency, remains the main challenge facing students of animal flight.

Finally, why is it that the bumblebee has such small wings? The answer must lie in the bee's flight ecology, that is in the way it uses flight to gather nectar and pollen. This can lead it to carry large loads, for which small wings are not especially suited[8,10]. Hummingbirds (and also some species of bats) also feed on nectar, often hovering by host plants, and also have smaller wings than expected for their size[8,10]. In these vertebrates the explanation seems to be the need to fly fast to defend large territories and to minimize time in commuting flights; the same explanations seem equally plausible for bumblebees. □

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MATERIALS TECHNOLOGY

The power of paradox

Robert W. Cahn

SCIENCE progresses by the resolution of paradoxes. Interpretations of the nature of light swung back and forth — particles or waves? — until the quantum synthesis embraced both absolutes. A door must be either open or shut, the logical French tell us. But a liquid crystal is neither solid nor liquid; a quasicrystal, neither crystalline nor amorphous; a magnetic 'fluid' can be either mobile or rigid. The best doors are both open *and* shut.

So it is with strength. Ceramics are much stronger than metals: but drop a plate on the floor and it shatters, drop an aluminium bottle and it dents and survives. What really matters is toughness, the ability to resist shock, to break gradually rather than catastrophically, to give adequate warning of impending disaster. Brute strength will not suffice. The introduction of fibre-reinforced composites — arrays of strong ceramic fibres in weak polymeric matrices — as a practical way of taming the brittleness endemic to ceramics expressed the principle of "strength made perfect in weakness", to cite an apposite biblical paradox. The fibres arrest cracks which try to spread through the polymer, and also carry most of the load. But polymers will not stand up to red heat.

Now, as reported elsewhere in this issue (W. J. Clegg, K. Kendall, N. McN. Alford, T. W. Button, & J. D. Birchall, *Nature* **347**, 445–447; 1990), a group from the ICI Advanced Materials Laboratory has found a new way of creating toughness by marrying strength and weakness; their way produces a composite material which is relatively cheap to make and moreover contains only components resistant to high temperatures. The combination of intrinsic ceramic strength and heat resistance with both toughness and cheapness is something new.

Clegg and his collaborators have prepared blocks consisting of silicon carbide layers, separated by thin graphite interlayers. Graphite in itself is far from weak — in the form of carbon fibres, it is one of the strongest materials known — but here it forms a weak interface: a crack in the SiC impinging upon the interface becomes diverted so that it carries on spreading along the interface, dissipating energy as it does so. Silicon carbide and graphite are both strong but the interface between them is weak in shear, not in tension or compression: strength made perfect in weakness. The material, in fact, behaves very much like nature's own favourite composite, wood.

The composite is made by mixing silicon carbide powder, doped to aid sintering, with a concentrated polymer solution in a special high-shear processor. The ICI team had previously developed both the solution and the mixer to make ultrastrong cement. The resulting SiC paste, in the form of 2-mm sheets, is rolled out like dough into layers 0.2 mm thick, coated with graphite, stacked in tenfold multilayers, slowly dried out and sintered. Graphite, we are told, has the crucial property of not reacting with stoichiometric SiC, which can dissolve no excess of either of its constituents. For comparison, the authors also sintered unrolled, uncoated SiC sheets.

Slow bend tests at ambient temperature show, for the composite, gradual fracture with repeated load drops as incipient transverse cracks on the tension side are diverted to spread laterally along SiC/graphite interfaces. A specific work of fracture — one test of toughness — ranging from 4,600–6,700 J m^{-2} was recorded, compared with a value of only 60 J m^{-2} for the monolithic (non-composite) material (a figure further reduced by a technical correction to 30 J m^{-2}). The composite is thus more than a hundred times tougher than the monolith, at least in bending and at room temperature. The stress at which failure begins in the composite is reduced by 25 per cent, however: every benefit has its price.

The work of fracture of the composite is slightly higher than that of the hardwood, deal. So the ICI team has improved upon nature in two ways: their material is tougher than hardwood and it can certainly be safely heated to red heat. Whether the material maintains its strength and toughness at high temperature we are not told.

The new material is, in effect, a ceramic/ceramic composite. Others such have been made before, but only by expensive methods such as gas-phase reactions which take months to make what the ICI method produces in hours. Carbon/carbon composites (S. E. Hsu & C. I. Chen in *Superalloys, Supercomposites and Superceramics* (eds J. K. Tien & T. Caulfield) 721–744; Academic, New York, 1989) are an exception: they are an industrial product category in actual use, and are made by impregnating woven carbon fibre structures with liquid or gaseous polymeric or other organic precursors. However, they are mostly used for applications such as rocket nozzles or fighter wheel-brakes for which cost is scarcely considered. Very strong microlayered aluminium/transition metal composites have been made at the Royal Aerospace Establishment in Farnborough by vapour deposition: this kind of alloy is very strong and tough but seems for the time being to have faded from view, perhaps because of its exorbitant cost.

Clegg *et al.* point out that their new technique is not restricted to making sheets. For instance, wires of SiC/carbon composites can be extruded from the paste and then coated and pressed together to make rods. But the real novelty of the approach is undoubtedly the probable cheapness of the processing method. □

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