Materials science

Nuts to tough ceramics

Paul Calvert

MACADAMIA or Queensland nuts are much used in high-class cookies but are very difficult to remove from their shells without special equipment. In a recent article, J.S. Jennings and N.H. Macmillan (*J. Mater. Sci.* **21,** 1517; 1986) discuss the properties of the fibrous macadamia nutshell and shed some light on the prospects for fibre-reinforced ceramic materials which are currently thought to be the route to tough ceramics for use in engine components.

Jennings and Macmillan looked at the microstructure of the nutshells and measured the mechanical properties of various sections of the shells in the wet and dry states. It is very difficult to obtain reproducible mechanical measurements on biological materials because the properties are frequently dependent on the age and moisture content of the tissue and vary with orientation and position in the organism as well as being vulnerable to flaws. This creates something of a philosophical problem for engineers who are faced with a natural system, when they are more used to uniform properties measured on large pieces of material. In this (nut) case the properties are surprisingly uniform and are best described as those of 'isotropic wood'. That is, the moduli, strength and toughness are comparable with the geometric averages of those parallel to the grain and across the grain of a softwood. A nice recent example of this grain effect is a study of kelp (Vincent, J.F.V. and Gravell, K. *J. Mater. Sci. Lett.* **5,** 353; 1986), which forms 'leaves' by the tearing action of the sea along the weak direction parallel to the fibres. The work of fracture decreases by 500 times from fracture across the fibres to fracture parallel to the fibres.

The Young's modulus (elasticity in tension) of the nutshells is about 5 GPa, where wood is about 10 GPa parallel to the grain and 0.5 GPa across the grain. The (fracture) strength of the shells is 50–80 MPa, where wood is about 100 MPa along the grain and 5 MPa across. In terms of a complete nut this corresponds to a hungry gourmet needing to exert about 50 kilos of force on a normal pair of nutcrackers. The fracture toughness is calculated from the stress needed to propagate a crack in a notched sample, and is thus a measure of one's ability to open the nut by making a small cut and levering on it. This value is in the range from 0.8–2 MPa $m^{1/2}$ for the nutshell whereas wood is 1 and 2 MPa $m^{1/2}$ parallel and perpendicular to the grain, respectively. As Jennings and Macmillan point out, these properties are not terrific when one takes into account the fact that the density of nutshells is 2.5–3 times that of wood. The advantage of this design seems to lie in the isotropic properties which ensure that the shell is not weak along any particular direction and so cannot be split like wood, on the same principle that plywood gains strength by having layers with crossed grains. This toughness precludes attacking the nut by a shrewd wallop with a hammer and chisel.

The shell is made up of fibrous cells, each about 30 μm in diameter, which are arranged in bundles of tens or hundreds of parallel rods. The bundles then pack to fill the volume. When the shell breaks, the fracture either goes through the rods or around them, depending on whether the crack is perpendicular or parallel to the rods. The toughness then arises from the need for the crack to change direction as it traverses the shell, possibly with some microcracking within and around the fibres that significantly adds to the energy needed to drive the crack. This is illustrated by recent work of A.R. Sanadi, S.V. Prasad and P.K. Rohatgi (*J. Mater. Sci. Lett.* **5,** 395; 1986), who looked at fracture of polyester resins reinforced by fibres of sunhemp. They observed extensive splitting and deformation of the fibres during fracture of the composite, and argue that this would give higher toughness than found in an equivalent composite reinforced with a brittle fibre such as glass. The sunhemp composite has 15 times the work of fracture of the polyester resin alone.

At a recent meeting on ceramics in Pennsylvania, United States (15–19 June 1986), A.G. Evans (University of California, Berkeley) summarized the requirements for the successful application of ceramic (for example, alumina or silicon nitride) parts in engines. These were a toughness of 20–25 MPa $m^{1/2}$, a strength of 300 MPa and a creep strain of less than 1 per cent at high temperature (>1,000°C). All these properties can be achieved, but not all in the same material at once and not reliably. The toughness of the ceramic can be raised by two methods: one is to incorporate some tetragonal zirconia which raises the toughness by a martensitic transformation process similar to that in steel from 3–5 to 10–20 MPa $m^{1/2}$. This has the disadvantage that the toughening is not stable to high-temperature treatments. The second is to incorporate fibres or whiskers of another ceramic to make a ceramic-toughened ceramic composite. Because we want to make moulded parts rather than bars or sheets, the fibres must be randomly oriented to produce a structure very similar to that of the macadamia shell. This structure is quite different from conventional composites where the fibres are either all parallel or are arranged in layers and where a hard, strong fibre is used in a soft but tough matrix, as in glass-fibre reinforced plastics.

Silicon carbide whiskers about 0.6 μm long are commercially available from pyrolysed rice hulls. These whiskers have been used to reinforce alumina, producing a doubling in toughness to 6–9 MPa $m^{1/2}$. Because the system was hot-pressed, the fibres were in a random-in-plane orientation rather than isotropic. At loadings higher than 20 vol per cent, the whiskers did not increase toughness because they cause extensive cracking in the alumina during sintering (Wei, G.C. and Becher, P.F. *Am. Ceram. Soc. Bull.* **64,** 298; 1985). The questions that we now wish to ask the nut are: what is the maximum toughening we can expect from whiskers in hard matrix systems; and how can we achieve high loadings of fibres into an isotropic, packed-bundle arrangement? □

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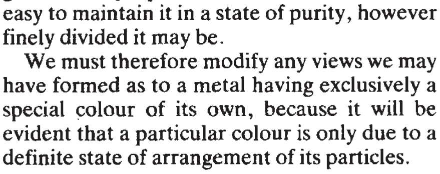
100 years ago

WE are apt to think of gold as being essentially and distinctively golden-yellow; it may, however, possess a wide range of colours. A leaf of gold when seen by transmitted light is either green or blue, according to its thickness. Here is such a leaf of green gold as seen when light is actually sent through it, so as to project a green disk on screen. A portion of the light will be *reflected* from its surface, and this reflected ray may be caught in a mirror and thrown on the screen so that you have, shown side by side, the green disk of transmitted light and the golden one of reflected light from the same leaf of gold.



It would be easy to show that light is similarly affected by other metals; but I have selected gold for the purpose of illustration because it is easy to maintain it in a state of purity, however finely divided it may be.

We must therefore modify any views we may have formed as to a metal having exclusively a special colour of its own, because it will be evident that a particular colour is only due to a definite state of arrangement of its particles.

From *Nature* **35,** 109; 2 December 1886.