Fractal dimension and fracture

Robert W. Cahn

How rough is a fracture surface? This question is in the domain of the craft of fractography, which seeks to elucidate the mechanisms of fracture by studying the topography of a broken object. Somewhat akin to phrenology, some skeptics might say. Nevertheless, in two new studies, Mecholsky, with Mackin and with Passoja and Feinberg-Ringel, shows that it may be possible to scale the fracture toughness of fairly brittle materials by just such an exercise in fractographic analysis, exploiting the concept of fractals.

Fractals were invented—or at any rate clearly formalized—by Mandelbrot. The term refers to any boundary or surface which remains self-similar as the scale of examination is magnified. Figure 1 gives an example of such a boundary. For this shape, a 'Koch island', drawn to be always of constant area, the length of the perimeter is increased by a factor of 1.5 from one drawing to the next, if the length of the ruler unit used to measure it is decreased by half, and the image resolution grows by a factor of four. If the logarithm of the total perimeter length is plotted against the logarithm of the length of the ruler unit (the resolution), a straight line or 'Richardson plot' is obtained, the slope of which was treated by Mandelbrot as a fractional, fractal, dimension: for a boundary as in Fig. 1, this dimension is between 1 and 2—in this case, 1.5.

Similarly, a rough surface which is self-similar has a dimension between 2 and 3. To obtain this fractal dimension, it is usual either to make serial sections perpendicular to the surface ('vertical' sections) and examine the shape of the section boundary, or to section parallel to the surface and examine the perimeters of the 'islands' and 'lakes' which are in effect contours of such 'horizontal' sections.

The original concept of fractals was restricted to self-similar outlines only, but more recently the concept has been extended to more ordinary boundaries and surfaces of varying roughness; thus, Fig. 2 shows four outlines generated by a rather involved computer algorithm, with four different fractal dimensions. In such cases, the corresponding Richardson plot has a straight central part with curved regions at either end. (Such shapes should really be called 'pseudo-fractals', but that term does not appear to have been used.) Stereologists still disagree about the appositeness of the horizontal section approach, but in a recent study of fracture surfaces of ceramics, Mecholsky and Passoja found that the horizontal and vertical methods gave closely similar fractal dimensions.

The studies of Mecholsky and colleagues on the relation between fractals and fracture were stimulated by two apparently independent initiatives. One was a fractographic study by Mandelbrot et al. of broken specimens of maraging steel. The impact toughness of 300-grade maraging steel in various states of heat treatment increases steadily as the fractal dimension of the fracture surface decreases towards 2 (it becomes steadily smoother). It is apposite that Mandelbrot should have been involved in this early study because, as he says, he coined the term fractal in explicit cognizance of the fact that the irregularities found in fractal sets are often strikingly reminiscent of fracture surfaces in metals (though not, for example, in glass). Although he does not say so, one should not lose sight of the fact that the word fracture has the same Latin root as fracture, and fractals have fractional dimensions.

The second study was by Beauchamp and Purdy, who examined the changes in fracture toughness and fracture morphology of chert (flint) as it is heat-treated at progressively higher temperatures. It turns out that chert heated to 500°C is considerably less tough than untreated material; the heated chert also has a much smoother surface. (This implies that heated chert is easier to chip and shape into tools, and indeed there is archaeological evidence that chert was commonly heated in prehistoric times.) Heating coarsens the exceedingly fine grain of the chert and also apparently enhances the strength of the intergranular bond: unheated chert fractures along the boundaries of the fine grains, heated chert breaks transgranularly. But the unheated material is nevertheless tougher because fracture is constrained to follow a very tortuous path.

Beauchamp and Purdy did not explicitly invoke the fractal concept in their study.
Bacteria that thrive in toluene

Howard Goldfine

TOLUENE is widely used in the laboratory to permeabilize and kill bacteria. Thus, the isolation of a bacterial strain described by Inoue and Horikoshi on page 264 of this issue1, which not only resists the toxic actions of toluene, but grows luxuriantly in the presence of emulsions containing up to 50 per cent of this solvent, represents a significant achievement. In a rich medium, Inoue and Horikoshi find that growth in the presence of toluene is about two-thirds as rapid as that obtained in its absence. It should, however, immediately be noted that the newly isolated strain only tolerates toluene rather than using it as an energy source.

The organism, identified as a strain of the gram-negative bacterium *Pseudomonas putida*, an organism known for its protein degradative capabilities, was isolated after screening 750 soil samples collected in Japan. The only hint concerning the site of its isolation is that the soil was obtained from Kyushu, Japan’s large southern island. It is not clear whether these soils are contaminated with organic solvents.

The isolation of organisms resistant to aromatic hydrocarbons and other industrial products has implications for biodegradation and biotransformation. The annual global production of benzene and toluene each exceeded 104 gallons in 1980, and these materials are likely to be found in soils and sediments4. The availability of organisms that can withstand the toxic effects of these organic solvents and participate in their degradation or transformation is clearly desirable. *P. putida* contains chromosomal genes encoding the enzymes involved in the degradation of aromatic compounds by the so-called ortho cleavage pathway, and strains have been isolated that contain the common TOL plasmids encoding the genes for the enzymes of the catechol meta cleavage pathway. It would seem to be just a short step to bring together these degradative resistance characteristics. The isolated strain is also resistant to styrene, p-xylene, ethylbenzene, cyclohexane, o-dichlorobenzene, propylenebenzene and various alkanes up to isooctane, thus there is wide scope for producing both solvent-tolerant and solvent-degrading strains. The marriage of these two desirable traits may be less than harmonious, however. The alterations in the cells of the toluenetolerant strain that make growth in solvents possible could shield the cell from these solvents so perfectly that little penetration to the locations of degradative enzymes would be possible.

The authors of the paper in this issue, one of whom is a member of the Superbugs Project of the Research Development Corporation of Japan, have begun a genetic analysis of the solvent resistance of *P. putida*. They have isolated a series of mutants of this new strain that are not resistant to toluene, but retain resistance to solvents of lower polarity in the order toluene > p-xylene > cyclohexane > hexane.

By examining the partitioning index of these and other substances in a standard octanol:water mixture, they can predict accurately the resistance of these mutant strains to other compounds in the polarity scale. In addition to mutant strains of *P. putida*, they can order other microorganisms in a similar hierarchy of solvent tolerance, in which growth in a solvent of a given polarity indicates tolerance to solvents of lower polarity. Genetic analysis combined with biochemical and morphological studies should provide useful insights into the nature of solvent tolerance in these bacteria.

The outer membrane of gram-negative bacteria is important in determining the penetration of hydrophobic molecules through cell membranes, and consequently in determining the resistance of these bacteria to dyes, detergents, bile salts and hydrophobic antibiotics. Mutations in the structure of the lipopolysaccharide of the outer membrane can profoundly affect permeability of these molecules, but these effects are complicated by concomitant changes in the amounts of specialized pore-forming, outer-membrane proteins5. Studies of the outer membranes of these solvent-resistant strains of *P. putida* may be rewarding.

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