SureScreen Scientifics

Technical Bulletin
Issue 4

BRITTLE FRACTURE

Most people can name a few brittle materials. Glass. Bone. Peanut brittle. But look no further than your pantry for examples. Jelly is brittle. Chocolate is brittle, and you'll probably already know that most glass and crockery is brittle.

So what do these all have in common? They all have limited means of deforming, and the energy needed to initiate a fracture is greater than the energy needed to propagate fracture. So once a crack forms, it goes on to complete the fracture, and fast too, generally around the speed of sound. That's what makes brittle fracture catastrophic, causing sudden failure without warning. The dictionary definition of brittle is 'hard but liable to break easily'.


Peanut brittle epitomises 'brittle'

When materials deform their atoms have to slip over each other as planes of atoms glide like pages in a book when you twist its covers. Materials with limited slip systems have difficulty deforming, allowing stresses to rise to the critical levels needed to initiate a crack. Anything that limits slip will make a material more brittle. Glass (silica, toffee, peanut brittle) and even raspberry jelly have almost no slip systems that operate, so they're 'brittle'. It's nothing to do with strength, and all to do with capacity to deform.

The main factor driving brittle fracture is temperature. As temperature rises, the atoms in the material vibrate more, allowing stressed atoms to jump over each other with greater ease. This is seen on the outside of the material as plastic deformation, a common feature of ductile fracture. At lower temperatures atom vibration decreases, and the atoms do not want to slip to new locations in the material. So when the stress on the material becomes high enough, the atoms just break their bonds and don't form new ones. This decrease in slippage causes little plastic deformation before fracture. You've probably seen a mad scientist freeze a rubber pipe in liquid nitrogen and smash it to smithereens with a hammer on TV. Same thing happens with a finger, we're told, but don't try that at home. In between, we have a ductile-brittle transformation temperature, known as DBTT. We'll come back to that later.

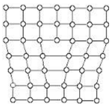

Forget fingers, a banana out of the freezer works just as well.

Sudden fracture makes brittle fracture so scary. There's usually no warning, and no defect that could be repaired to prevent disaster.

From 1942 around 2,700 Liberty ships were produced in USA in their $31.4billion (£267 billion in today's terms) 'lease-lend' programme to the UK at 2% interest. Britain's final payment of £42.5 million was paid on 29th December 2006, proving just how expensive and long lasting the effects of war can be.

Towards the end of the war these 14,000 ton ships could be fabricated and completed in just seven days. Such demand required a new fabrication method - welding. Now, cracks that would have stopped at the edge of a riveted plate could unzip a complete monocoque hull in an instant. Brittle fractures travel at 14,000 kilometres a second, so no time to shout 'Abandon Ship'.

In just two years some 94 ships suddenly broke in two, mostly from the stress concentration at the corner of the square hatchways. The ship seen here was repaired and gave good service. These failures were all in North Atlantic water, with none in tropical waters, giving us an insight into the effects of temperature on brittle materials. We'll never know how many of the 300 ships lost without trace in the North Atlantic were blamed on U-boat attacks.



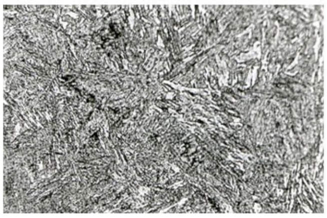
When metal is cold-worked, slip in atomic planes pile up causing errors in atom stacking known as dislocations, shown by the extra plane of atoms in this image. Metals naturally have around 10^{10} of these dislocations per m^2 and this can increase to 10^{16} dislocations per m^2 in heavily worked metal. Piled up dislocations make metal less able to deform, so work it too much and it will become brittle. It's a bit like stapling pages together in that book we mentioned earlier, making it harder to twist the covers.

That's why metals have to be annealed from time to time as they are worked, allowing atoms to reorganise and dislocations to heal. Hot working is fine because the heat allows dislocations to reorganise themselves as the metal deforms. Dislocation density increases metal resistance to deformation, so harder materials are inherently more brittle.

Brittle fracture is all about the ability of dislocations to move around in the material

Another factor is grain size. As grains get smaller in a material, the fracture becomes more brittle. This is because in smaller grains, dislocations have less space to move before they hit a grain boundary. When dislocations can't move very far before fracture, plastic deformation decreases, so the material's fracture mode is more brittle.

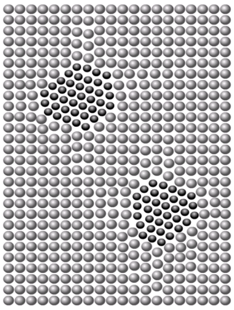
Armed with these insights, we can predict how different features will affect the material. Crockery is crystalline, with a strongly ordered structure. Drop it and it breaks. Glass is amorphous solid, with no slip systems, so it fractures in a brittle manner when stressed. Silica glass has quite a high coefficient of expansion, so it cracks when heated unevenly and will fail miserably as a teapot. Borosilicate glass has a small coefficient of expansion, and can have its composition adjusted to have almost zero coefficient so as 'Pyrex' glass it's used for cooking utensils. Your car headlights are Pyrex, though the latest LED headlights produce less heat. Chocolate has no slip systems, and behaves in a brittle manner unless warm. It fractures easily, aided by the convenient notched surface. Try breaking it from the flat side and you'll find it's much more difficult, especially if tested straight from the fridge. With Mars sales alone of $17billion a year there's a lot of testing of chocolate going on. Two critical factors are the transition between brittle and ductile, and the melting point. That's why Hershey's chocolate is very different to Cadbury's chocolate, it's designed to survive Texas temperatures, but it's still useless as a teapot.



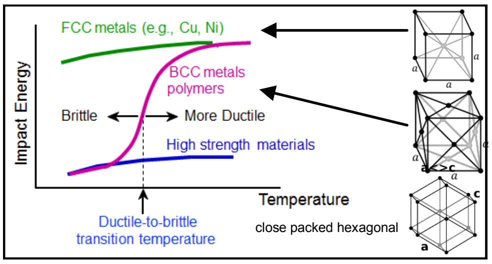
Some metal microstructures are quite rigid, pushing the metal towards the brittle zone. Include highly stressed structures such as martensite (shown here) in this category. Case hardened gears have a brittle carburised shell that is prone to cracking under impact, while the softer core usually survives.

Cars from the 1960's had through-hardened gears, causing them to lose chunks especially in crude 'crash gearboxes' without synchromesh on first gear. That's the real cause of the 'wow-wow-wow' of a Morris Minor gearbox as it pulls away in first gear.

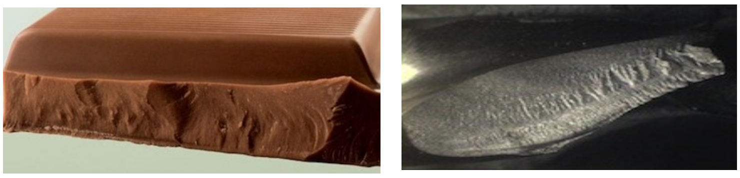
Those metals with a lot of precipitates, such as high carbon steel, are also more brittle especially when cold. And carbon steels with their body centred cubic atomic structure are more easily pinned by precipitates than the face centred cubic structure of austenitic stainless steels. Some metals, notably magnesium, zinc and titanium are hexagonal close packed and have many slip systems. Graphite is planar rhombohedral, in layers, making a monolayer flexible graphene film possible, but when hardened with clay for pencil leads, it becomes irritatingly brittle as its clay content and hence hardness rises.


The effect of precipitates in pinning dislocations. Its like glueing book pages together to make it more rigid.

The speed of impact also pushes materials towards embrittlement, providing less opportunity for macro-deformation to occur. We owe the impact test that is used to classify metal toughness to American SB Russell who in 1898 proposed a high speed impact test on plain specimens to measure ductility. Frenchman George Charpy, who gained a degree in military artillery in 1887, refined this into the standard notched specimen we use today. The test was used to help understand the problems with Liberty ships, generally leading to improvements in the toughness of modern metals. Some metals, such as bells, forges and jack hammers are impacted at speed, but in others, speed of impact in the Charpy testputs an overly pessimistic value on the performance in real life.



One use of Charpy tests is to define the ductile-brittle transition temperature (DBTT) of steel. Impact sets of three Charpy specimens at different temperatures and plot results to find the temperature at which the DBTT occurs. Operate body-centred cubic (BCC) mild steel above the DBTT to avoid a catastrophe. Recent tests on steel from the hull of Titanic has shown it was brittle at the near-freezing temperatures in the North Atlantic that April. Chocolate has a DBTT as it is devoid of slip systems, but as the graph shows, face centred cubic metals like copper and austenitic stainless are immune. That's why cryogenic containers are made of stainless steel.


Choicolate and a fractured drill bit share similar brittle fracture river marks due to cleavage

Contaminants are another factor in brittle fracture. The steel used to fabricate the Titanic had a high sulphur content. Carbon, nitrogen and sulphur increase embrittlement and raise the DBTT. That's not surprising, as these additives sit uncomfortably in the metal lattice, making movement of dislocations more difficult.

FRACTURE MECHANICS

$$C = \sqrt{\frac{2E\gamma}{\pi}}$$

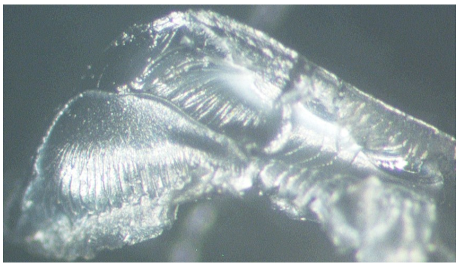
All materials have inherent defects of some kind or other, and in brittle materials the critical defect size can be very small. The Griffith crack opening energy equation that is the fundamental theory around fracture mechanics can be used to predict brittle instability, but another factor plays a key part and it's known as triaxial stress. In the Griffith equation the critical crack length is C, E is Young's Modulus and gamma is the surface energy density (=1 for most materials).

Thin sections are free to deform, but rigid structures such as thick sections, bends, pipes and substantial welds have their movement restricted by the mass of rigid metal that surrounds them. This prevents the structure from yielding to even out stresses - known as 'stress shakedown' and without that effect local stresses can and usually do exceed the yield strength of the metal. Large structures can be stressed so much in critical areas that they will fail suddenly in a brittle manner, simply because of the inability to yield. Charpy testing uses standard 10mm cross sections which fail to take triaxial stressing into account.

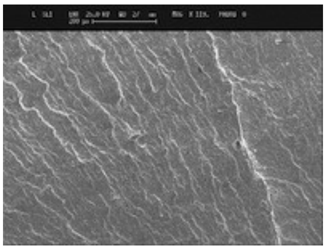
FRACTURE FACES AND MICROSTRUCTURES

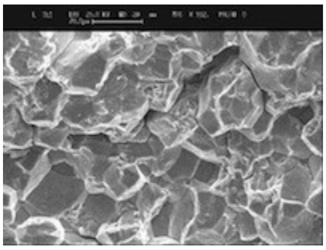
When brittle fracture occurs, a series of cleavage lines develop on the surface, fanning out from the origin like a river delta, so they are often called 'river marks'. In addition, a series of concentric marks called conchoidal marks (named after the pattern on a Conch shell) radiate out from the origin. Often it's one or the other depending on the cleavage characteristics, but both are highly indicative of brittle fracture. It needs an expert eye to distinguish conchoidal fracture from fatigue fracture, but we are forensic scientists, and few people have the wealth of experience in the fracture examination of so many materials, from plastics, metals, composites and yes, even confectionery products. We are sometimes asked to determine whether the fracturing of a pane of glass was accidental or deliberate too, which is based on the amount of energy required to generate the crack surfaces. One job involved counting windscreen cracks to determine the speed of impact, requiring us to buy a car and test it at speed - scary.

The Griffith equation can be used to predict critical defect sizes


Brittle fracture of a plastic clip with river & conchoidal marks

Brittle fracture can be confusing, as the fracture can travel in a transgranular (across grains) mode or intergranular (round grains) mode. Sometimes electron microscope images ike those seen on the right help.





Some brittle fractures are the result of sudden shock or explosions. The extreme loading produces additional damage in the form of shock lines in the metal. These are called Neumann bands after Johann Neumann who first discovered them 1848 in an iron meteorite. We've seen them in metal from bomb blasts, and boiler explosions.

Hopefully, this information will help prevent problems in future, or might even alert you to an imminent disaster. Remember, we are here on call to respond to any questions or problems you may have. And we're well known for delivering advice that is simple to understand and easy to apply. Why not check out our other bulletins, or browse our extensive library of failures on www.scientifics.co.uk


Neumann bands in a meteorite

REFERENCES

Pictures from our archive or from our web views of failures, except for the meteorite, which is a Wikipedia image. We donate regularly to Wikipedia. 'Best Practice Technical Bulletins are available as downloads at www.scientifics.co.uk and www.surescreen.com has a range of equally informative bulletins on medical matters.

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