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’.

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 all about the temperature mode is more brittle. 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.

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 $31.4 billion (£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.

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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 have a maximum of $10^{16}$ 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.

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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 an ind ind flat surface disc and it’s much more difficult, especially if tested straight from the fridge. With Mars sales alone of $17 billion 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 synchronmesh 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.

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 the 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.surescreen.com.uk

REFERENCES
Neumann bands in a meteorite

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SureScreen has a range of equally informative bulletins on medical matters.

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.surescreen.com.co.uk and www.surescreen.com has a range of equally informative bulletins on medical matters.