NUTS & BOLTS

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Our Philosophy

New Hampshire Materials Laboratory *has one goal—to help you solve your technical problems at a reasonable cost. Tests help, but are not always enough. Our team of dedicated and experienced professionals has both the skills and the backup facilities to serve in the following:*

- **Failure Analysis**
- **Material Certification & Compliance**
- **New Product Testing**
- **Mechanical Properties**
- **Tensile and Compression Testing**
- **Heat Treat Problems and Verification**
- **Reverse Engineering**
- **Weld & Life Testing**
- **SEM & EDS**

Ductile & Brittle Fracture

Background

Brittle fractures and ductile fractures are two of the best known failure modes. In this issue we shall discuss examples of both types of failure. The discussion applies equally well to metals, plastics, ceramics, our bones and teeth, and cracking an egg for breakfast. Brittle fractures and ductile fractures should not be confused with fatigue fracture which involves cyclic loading. Here, we are talking about fracture due to a single load application, recognizing that a single load fracture event is usually the end of a fatigue fracture.

The factors that control both brittle and ductile fracture revolve around the energy that must be provided to extend the fracture by a microscopic distance and the amount of elastic strain energy that is concurrently made available by that microscopic crack extension. If the elastic strain energy being released exceeds the energy required for crack extension then bang—we have spontaneous fracture!

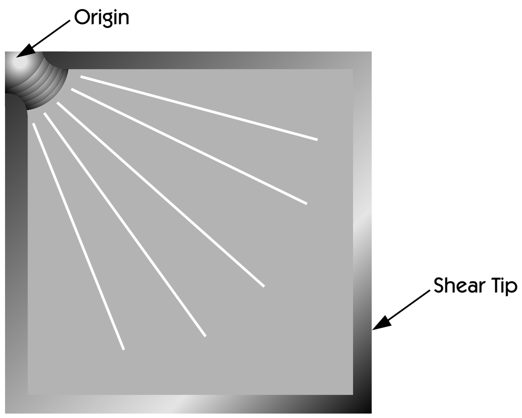

FIGURE 1: Sharp stress concentration

The crack stops growing either when it reaches the end of the part (the part breaks), or the energy required for crack extension exceeds the strain energy being released by that same crack extension and we have crack arrest. This happens, for example when a crack grows through an area under tensile stress and then stops when it runs into an area of stress that is reduced or compressive.

Understanding Fracture

Understanding fracture is a tall order. Required are understanding of both the energy required for crack extension and localized stress and strain. Since we are dealing with a difference, high accuracy is required for both energies if we are to be able to make quantitative predictions.

Quantitative predictions are also dreadfully important! It's OK for a crack to slowly grow across the wing of an aircraft until it reaches a size where it will be picked up during routine inspection. But society doesn't tolerate having the crack reach critical length before it is detected and fixed.

The Griffith Theory

Serious progress on these concepts appeared in 1920 as the Griffith Theory. The theory came on the heels of excellent research into the cleavage of high purity, three dimensional, crystals ranging from rock salt to diamonds and the cleavage of weird, two dimensional, materials such as mica.

Over time, it was found that Griffith Theory pretty well encompassed the fundamentals of the strain energy part of the fracture equation. That part of the equation is known as "fracture mechanics" and slow but steady progress was made through the first half of the 20th century. Spectacular progress appeared starting in the 1950's and continues to be made as both computers and electron microscopes improve.

But the crack extension energy side of the Griffith equation applied only to "ideally brittle" materials. Believe me, it was not for lack of research that the materials research community failed to extend fracture theory into the very important field of ductile fracture.

WWII Merchant Ships Etc.

Ships Break In Two! This was an extremely serious problem in World War II, when over 250 ships fractured or cracked. Nineteen of these broke completely in two! Luckily, in some cases, fractures occurred in ships that were being outfitted and had never put to sea. All of the ship fractures and the two other examples that follow were in metals that were ductile, but just not tough enough.

The Great Boston Molasses Tank Disaster One of the most famous brittle fractures was the Great Boston Molasses Tank Disaster in 1919. There was a tank of molasses, 90 ft in diameter and 50 feet high whose contents were supposed to have become rum. When the tank split, a wall of molasses advanced down the street. Many of the deaths and casualties occurred among people who were engulfed in their flats below the level of the street. There were 12 deaths and 40 injuries. Half a century later it was determined that the tank's steel was below its ductile/brittle transition temperature; the same problem as with the WWII merchant ships.

The Silver Bridge Collapse A more recent brittle fracture disaster was the collapse of the Silver Bridge in West Virginia, in December 1967 in which 46 people perished as their cars plunged into the icy Ohio River.

The National Bureau of Standards' metallurgists judged the bridge accident to be caused by stress-corrosion cracking resulting from long exposure to hydrogen sulfide vapor, H_2S, from nearby paper mill digesters. The bridge failure is an example where the energy required to extend the fracture was reduced while the metal was in service.

With the benefit of 20/20 hindsight, the ship hull and molasses tank accidents occurred when the steel's energy required to extend the fracture at service temperatures was too low starting when the metal left the steel mill.

Dislocation Theory

What made it possible to understand what was going on was the more or less simultaneous flowering of dislocation theory that explained how metals deform at the crack tip, and the development of the transmission electron microscope which let us *see* what was happening.

The Dislocation theory came together starting in the early 1930's while the electron microscope came from RCA in 1948. In the mid 1950's it was a hot research topic. By 1962 the field was sufficiently mature that the Air Force was requiring fracture analysis for critical components and by 1968 for almost all structural parts.

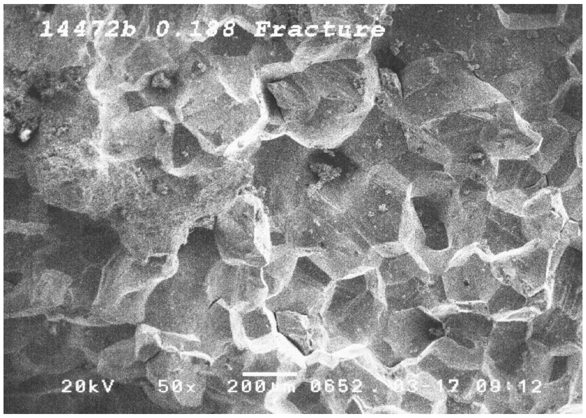

FIGURE 2: Intergranular fracture in a nickel-chromium alloy, viewed under the scanning electron microscope. Note that the fracture takes place between the grains; and that fracture surface has a "rock candy" appearance which reveals the shapes of the individual grains.

Some Characteristics of Brittle Fracture

- There is no gross, permanent deformation of the material.
- The surface of the brittle fracture tends to be perpendicular to the principal tensile stress although other components of stress can be factors.
- Characteristic crack advance markings frequently point to where the fracture originated.
- The path the crack follows depends on the material's structure. In metals, transgranular and intergranular cleavage are important. Cleavage shows up clearly in the SEM.

Some Characteristics of Ductile Fracture

- There is permanent deformation at the tip of the advancing crack that leaves distinct patterns in SEM images.

- As with brittle fractures, the surface of a ductile fracture tends to be perpendicular to the principal tensile stress, although other components of stress can be factors.
- In ductile, crystalline metals and ceramics it is microscopically resolved shear stress that is operating to expand the tip of the crack.
- The fracture surface is dull and fibrous.
- There has to be a lot of energy available to extend the crack.

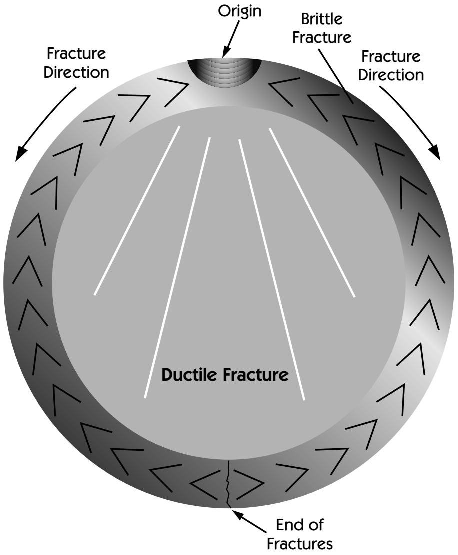

FIGURE 3: Ductile Fracture - If brittle fracture continues completely around the part, 2 separate fractures may form a step where they overlap opposite the origin.The interior, or core, is likely to have a ductile fracture, with dimpled rupture on a microscale.

Stress, Strain and Geometry

Surface Flaws We find we have to recognize that all engineering materials are endowed with surface flaws, and usually also internal flaws or discontinuities. All surface finishes, whether polished or machined or as-cast or grit blasted etc. introduce flaws that are characterized by an "effective crack length". If corrosion and/or wear is on going then the effective crack length increases with time in service.

For example, every feature on the pressure hull of a nuclear submarine is tested in the lab to determine its effective crack length. Considered are every size and shape of hull opening, every hatch corner, and every perturbation in either the inside or outside of the pressure hull. For the benefit of the folks on the CAD terminals, back at National Research Laboratories the critical crack lengths are converted to a telephone book of allowable design strengths.

Residual & Service-Related Stress We then consider both the residual stresses and the service-related stresses, noting that the material doesn't care which is which. Shot blasting introduces compression in addition to the applied stress. Grit blasting may introduce tension or compression in addition to the applied stress. Chromium plating may introduce a degree of tension that varies with plating practice with the plating tension added to the applied stress. Pre-bending introduces a residual stress pattern that is also added to the applied stress. These things account for the stress part of the equation.

Effect of Fracture Shape Next we consider the effect of the shape at the crack tip: rounded, sharp, internal with sharp corners on both ends, a vee running round a cylindrical part, an inside corner, a transverse hole, etc. We could convert these things into a "stress concentration" but history shows that doesn't work for either brittle or ductile fracture. Instead, *we use fracture mechanics to arrive at a "stress intensity" that merges all of these geometrical factors.*

Fracture Toughness

The other side of the equation is material properties that are merged to arrive at the "fracture toughness". Any of the following can bite you by reducing the material's fracture toughness. Some happen at the mill, some happen during manufacturing, and some happen in service.

The following list is taken mostly from steels. If requested, we can devote future Nuts & Bolts to other alloy, ceramic and plastic systems and we can flesh out these embrittling factors in steels .

Intergranular fractures are those that follow grain boundaries, weakened for whatever reason. Like a brick wall that fractures through the mortar rather than through the bricks. Examples of intergranular fractures include season cracking of brass by ammonia, liquid metal embrittlement during soldering, sensitization of stainless steels and phosphorous or antimony in hard steels.

Quench-age Embrittlement Cooling of carbon steels and low alloy steels from subcritical temperatures can precipitate carbides within the microstructure. The strength is raised but toughness is lost.

Blue Brittleness Within the range where blue-purple oxides can form on steels, 230-470°C (450-700°F), precipitates can form that increase the tensile strength and hardness while reducing the ductility and toughness.

Temper Embrittlement Quenched steels containing appreciable amounts of manganese, silicon, nickel or chromium are susceptible to temper embrittlement if they contain even trace amounts of antimony, tin or arsenic. Embrittlement of susceptible steels can occur after heating in the range 370-575°C (700-1070°F) but occurs most rapidly around 450-475°C (840-885°F).

Sigma-phase Embrittlement Prolonged service at 560-980°C (1050-1800°F) can cause formation of the hard, brittle, sigma phase in ferritic and austenitic stainless steels and similar alloys.

Graphitization This happens when the pearlite in steels begins to decompose into ferrite and graphite following very long, high temperature service, for example in steam power stations. For these applications a few steels turn out to be satisfactory while many others are subject to graphitization.

Internal Oxidation This is one of the common failures in high temperature, oxidizing conditions. You'll know you've got it when your wood stove cracks.

Intermetallic-Compound Embrittlement Intermetallic compounds can form inside a metal or ceramic when certain other metals penetrate by diffusion. An example would be galvanized steel where the zinc has diffused into the steel in the vicinity of 420°C (787°F).

Hydrogen Embrittlement Hydrogen is a whole subject unto itself, having several origins and several different effects, most of them bad. If you're interested, look back at the Nuts & Bolts on this topic. Let us know if you need a copy.

Order-Disorder Reactions While these embrittling reactions at the crystal level are not common in steels they are very common in non ferrous alloys.

Everything you ever wanted to know about...

Ductile & Brittle Fracture

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