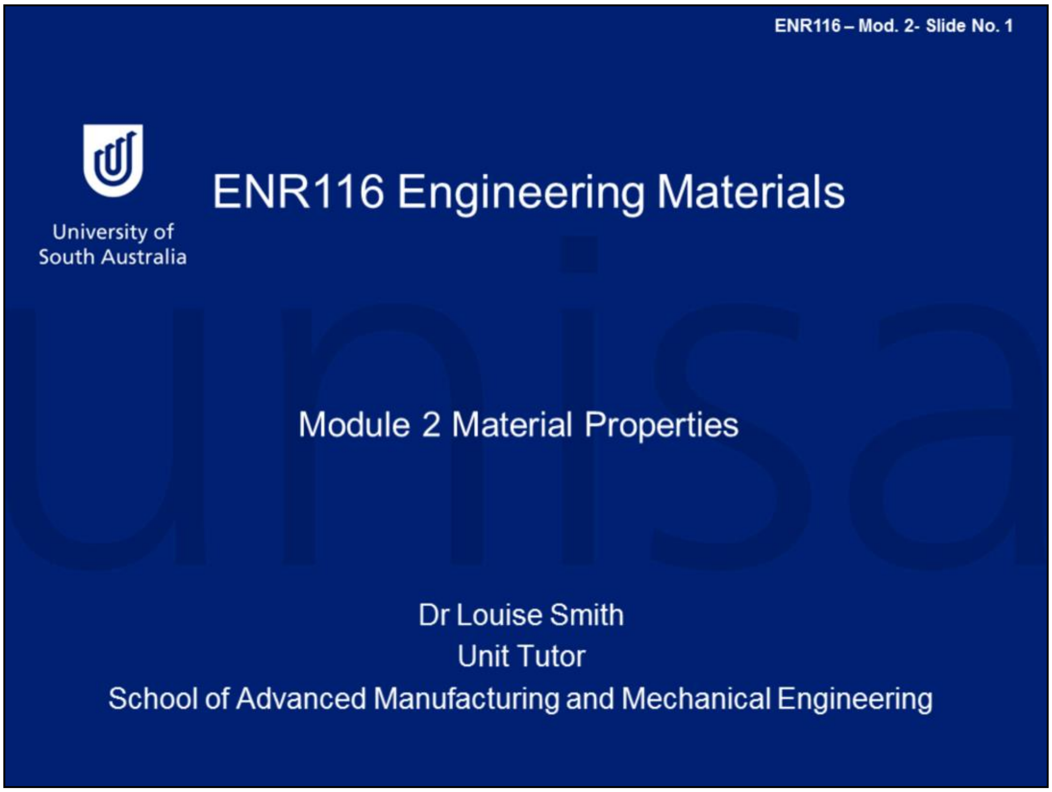

Welcome to ENR116 Engineering Materials. This lecture summary is part of module 2, Material Properties. I’m Louise Smith and I will be presenting this lecture summary.

Please take a moment to read this copyright notice.

This lecture summary is on fracture.

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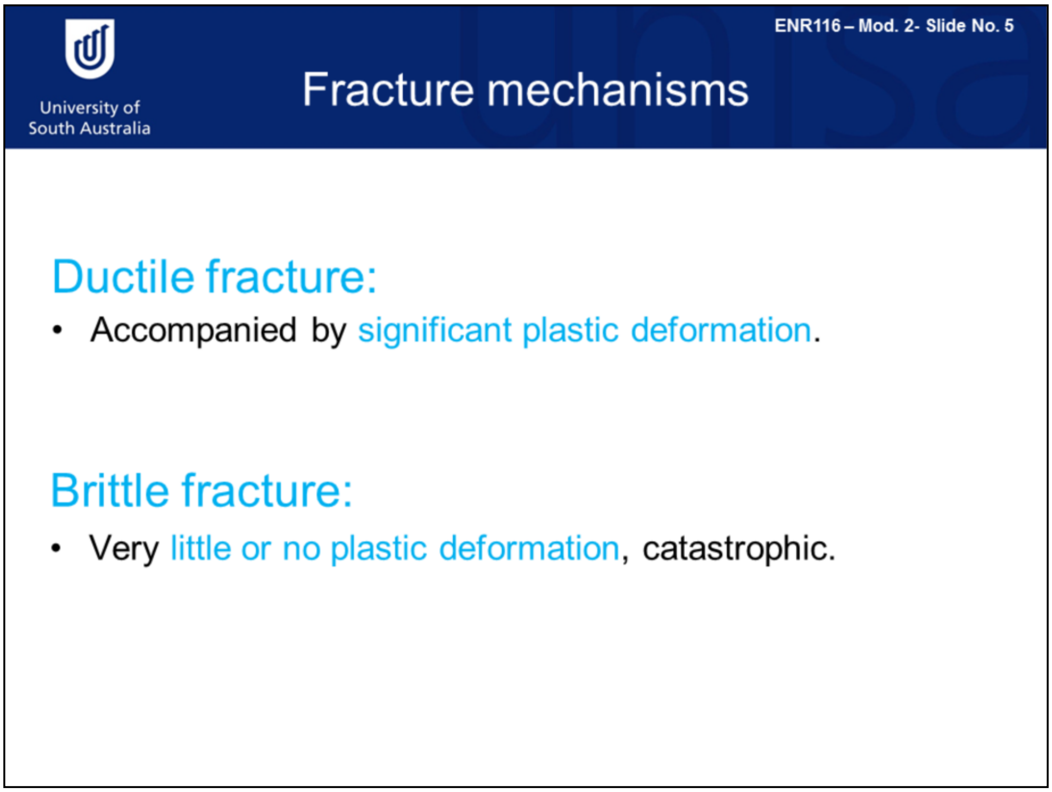
Intended Learning Outcomes

At the end of this section, students will be able to:-

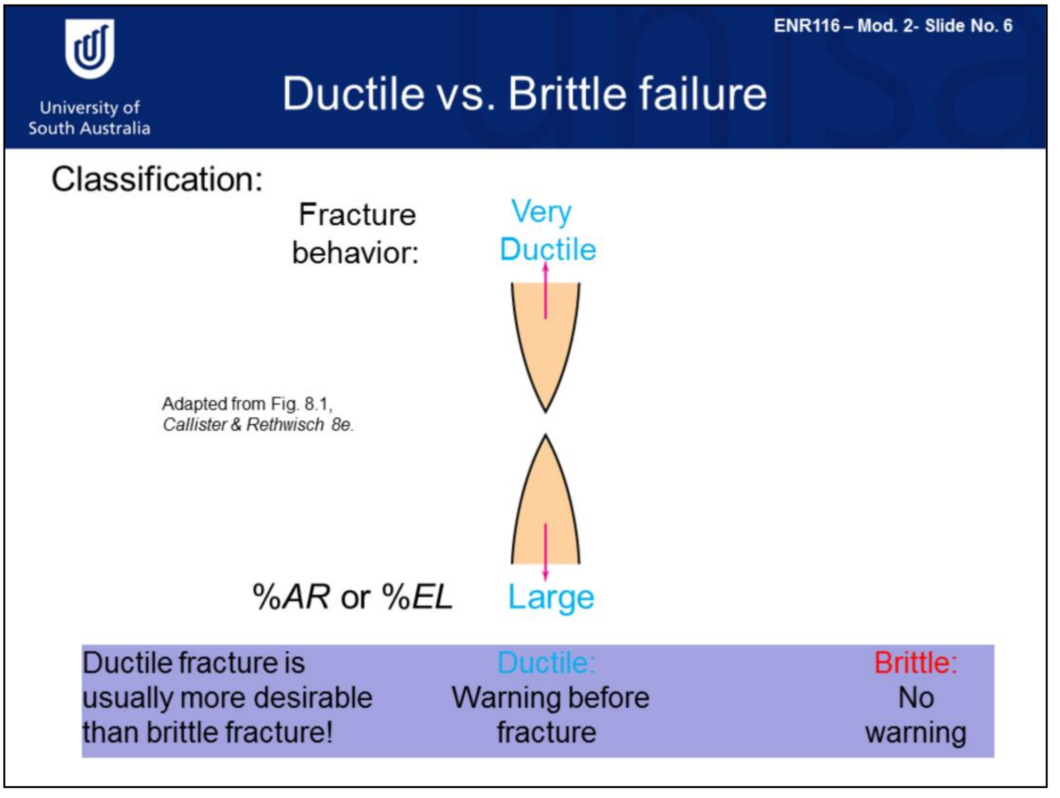
- Understand why materials are not as strong as theory predicts.
- Identify the types of flaw and their involvement in failure.

The intended learning outcomes from this lecture summary are that you will understand why materials are not as strong as theory predicts that they should be. You will also be able to identify different types of flaw and how they are involved with material failure.

e intended learning outcomes from this presentation are to be able to ....



There are two main types of fracture. Ductile fracture and brittle fracture. During ductile fracture a significant amount of plastic deformation occurs. However during brittle fracture there is little plastic deformation. A term that often accompanied brittle fracture is sudden catastrophic failure.



A material that undergoes ductile failure usually exhibits a large percentage reduction in area or percentage elongation at failure. This is normally seen in very soft materials such as pure gold and lead and amorphous polymers. If the testing temperature is increased this behaviour can also be seen in other metals, other polymers and inorganic glasses. These materials can exhibit an almost 100 per cent reduction in area. There is normally plenty of warning prior to the material fracturing. Most materials show some form of moderately ductile fracture. In this case a moderate amount of necking or a slight percentage reduction in area is seen prior to failure. For the final type of failure brittle failure, failure is often sudden and catastrophic with little or no warning prior to the component failure. The material often shows very little percentage reduction in area during failure. For these reasons it is often more desirable that a material undergoes ductile failure rather than brittle failure.

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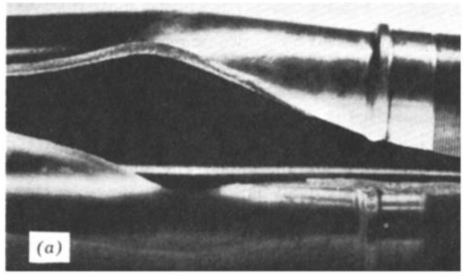
Example: Pipe failures

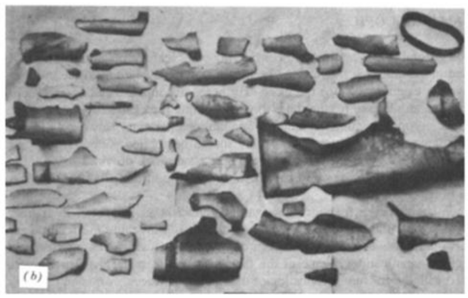
Ductile failure:

one piece
large deformation


(a)

Brittle failure:

many pieces
small deformations


(b)

Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

In these examples you can see two pipes. One has undergone ductile failure and the other brittle failure. The pipe that has failed in a ductile manner is still in one piece and there is a lot of deformation. The pipe that has undergone brittle failure is in many pieces, it almost looks like it has shattered or exploded. This failure was obviously sudden and catastrophic. The pipe undergoing ductile failure would have shown signs of failing prior to bursting and therefore there was the chance to make the pipe safe or remove it from the system. The pipe that has exploded could have potentially harmed anyone working nearby.

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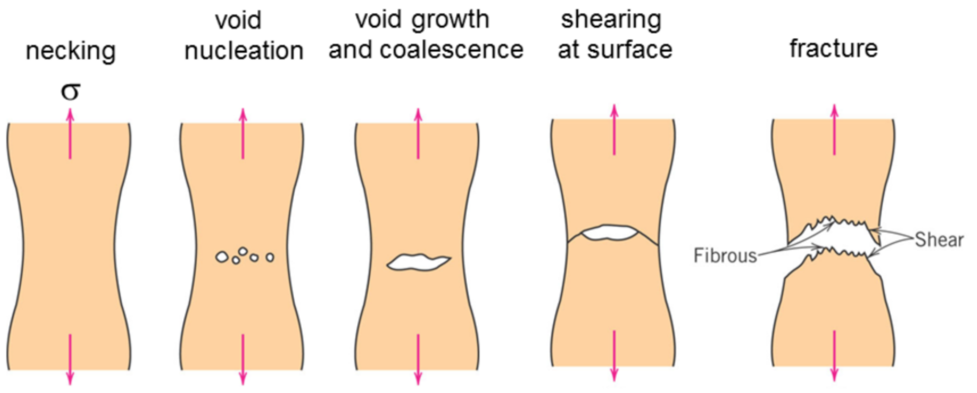
Moderately ductile failure

Failure Stages:



Adapted from Fig. 8.2, *Callister & Rethwisch 8e.*

There are a number of stages involved when a material fails in a moderately ductile manner. The material will initially start to neck. Eventually voids will start to form in the necking region. This is because the neck acts as a stress concentrator and so the stresses seen in this region are greater than the stresses seen in the bulk material. These voids will start to join up and then there will be shearing at the surface. Eventually the material will completely shear. This kind of fracture method is often termed a cup and cone fracture. The centre of the cup has an irregular or fibrous appearance and is often dull. This is indicative of the amount of plastic deformation that has occurred during the fracturing of this area. The edges are often shiny and smooth as this surface has fractured in a more brittle manner.

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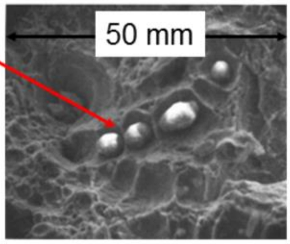
Moderately ductile failure

Resulting fracture surfaces (steel)

Particles serve as void nucleation sites.

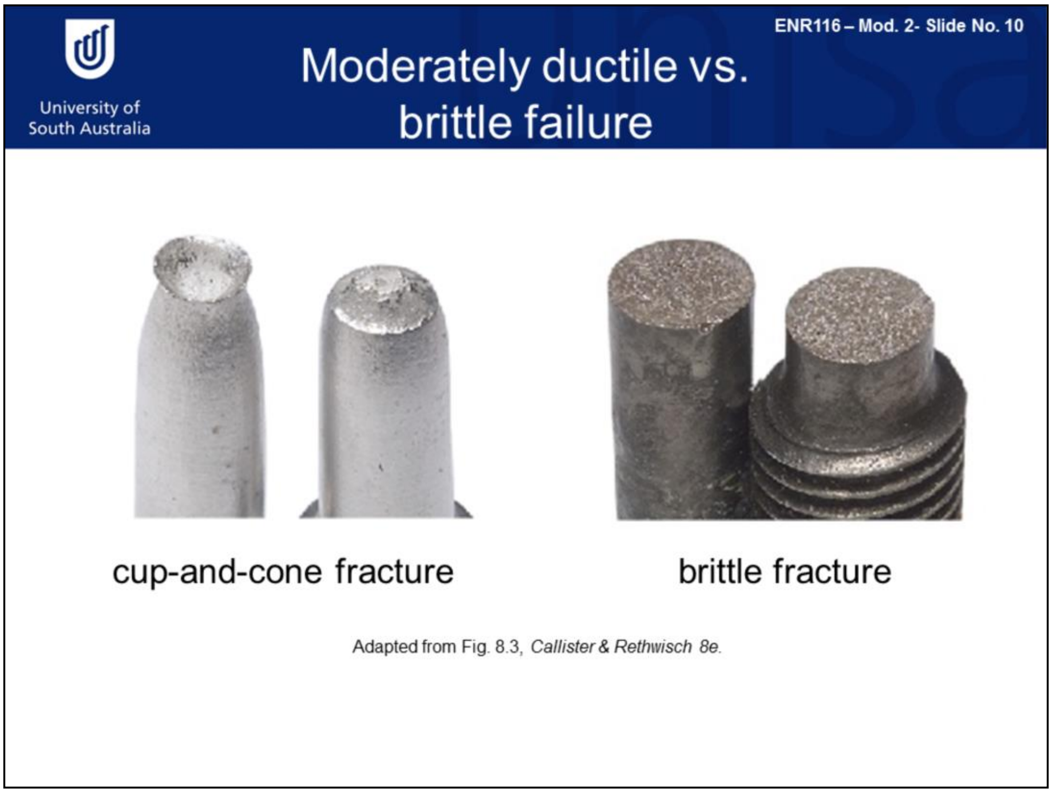


Ductile region

Brittle region

From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)

Looking at these this micrograph of a cup and cone fracture in steel you can see that the particles within the steel matrix have acted as void nucleation sites. You can also see the rough surface indicative of a large amount of plastic deformation. If you look at the second cup and cone fracture you can see the rough zone indicative of plastic deformation in the centre and the smooth outer edge of the cup is smooth indicative of rapid brittle failure.



Here you can see in metal specimens the difference between moderately ductile failure and brittle failure. The specimen that has failed in a moderately ductile manner shows the characteristic cup and cone behaviour. The specimen that has failed in a brittle manner has a flat, smooth surface. It shows no sign of plastic deformation.

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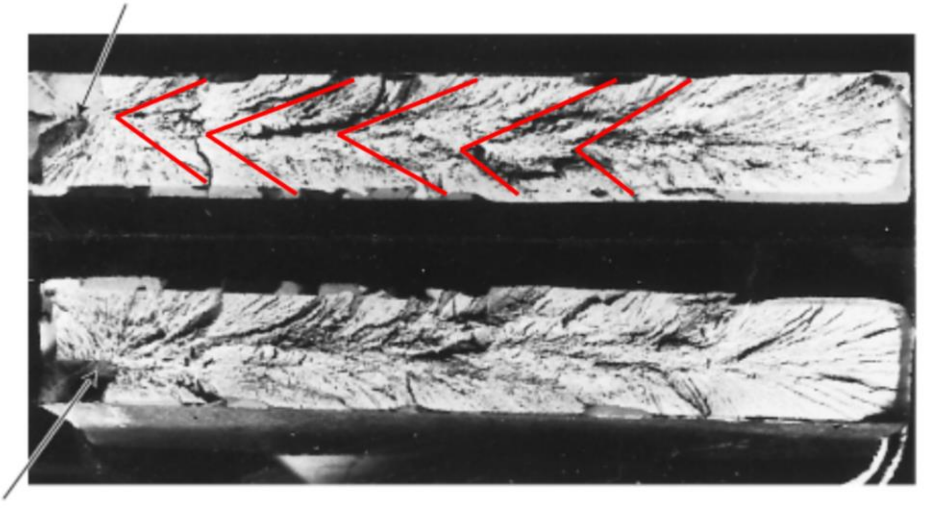
Brittle failure

Arrows indicate point at which failure originated



Adapted from Fig. 8.5(a), *Callister & Rethwisch 8e.*

Brittle failure occurs without any real amount of plastic deformation occurring. In some steel specimens, like those shown here there can be a number of chevron like markings that point towards the crack nucleation site.

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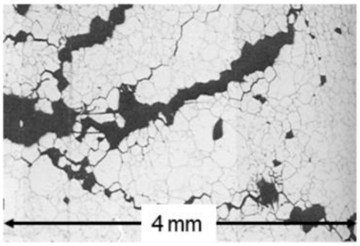
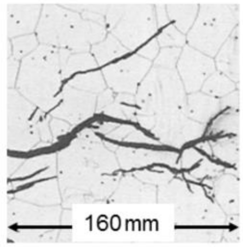
Brittle fracture surfaces

Intergranular
(between grains)



304 S. Steel (metal)
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

Transgranular
(through grains)



316 S. Steel (metal)
Reprinted w/ permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)

Cracks can propagate through brittle materials in one of 2 ways. They can go between grains or along grain boundaries, termed intergranular or go through grains, termed transgranular. These two micrographs show the difference between the two in metals.

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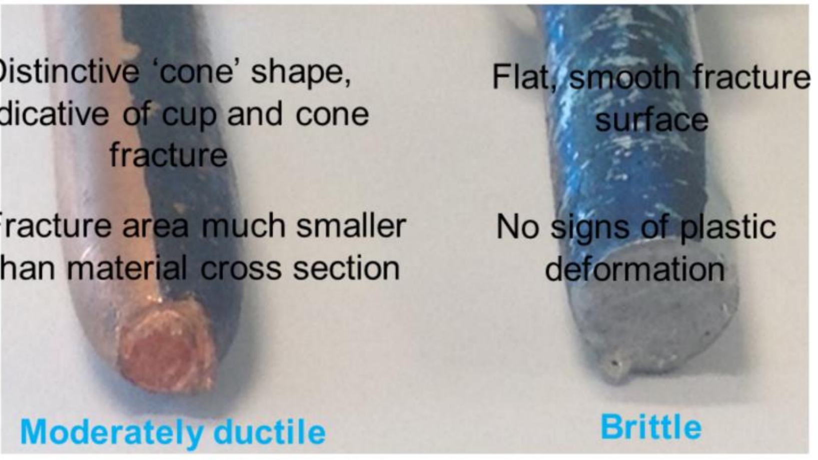
Test yourself: failure mechanisms

Please take a few moments to study these photographs. From the characteristics of each surface, what types of failure can you identify? (answers reveal automatically)



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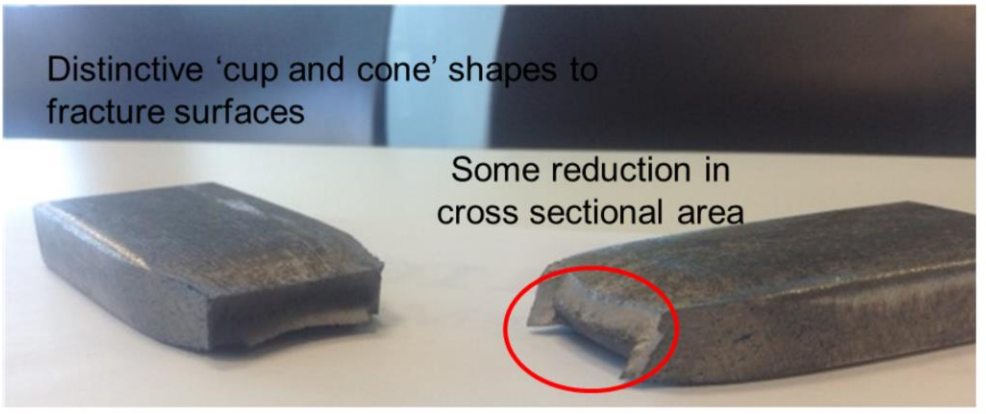
Test yourself 2: failure mechanisms



Moderately ductile

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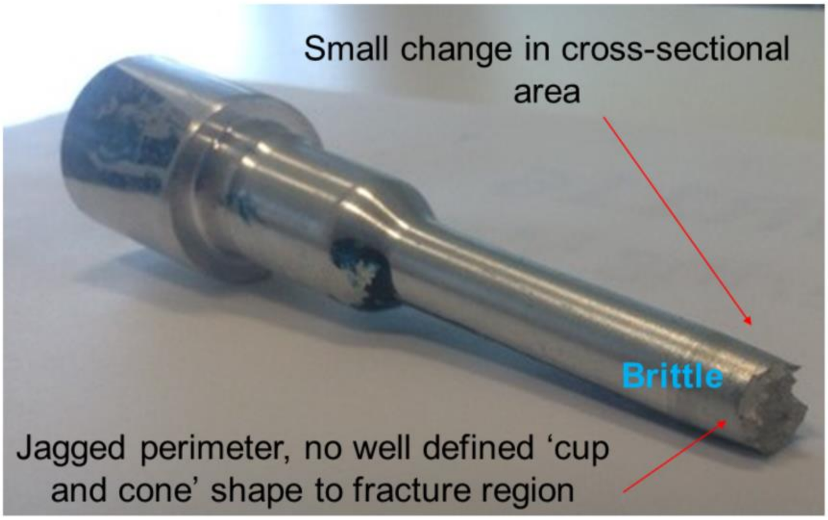
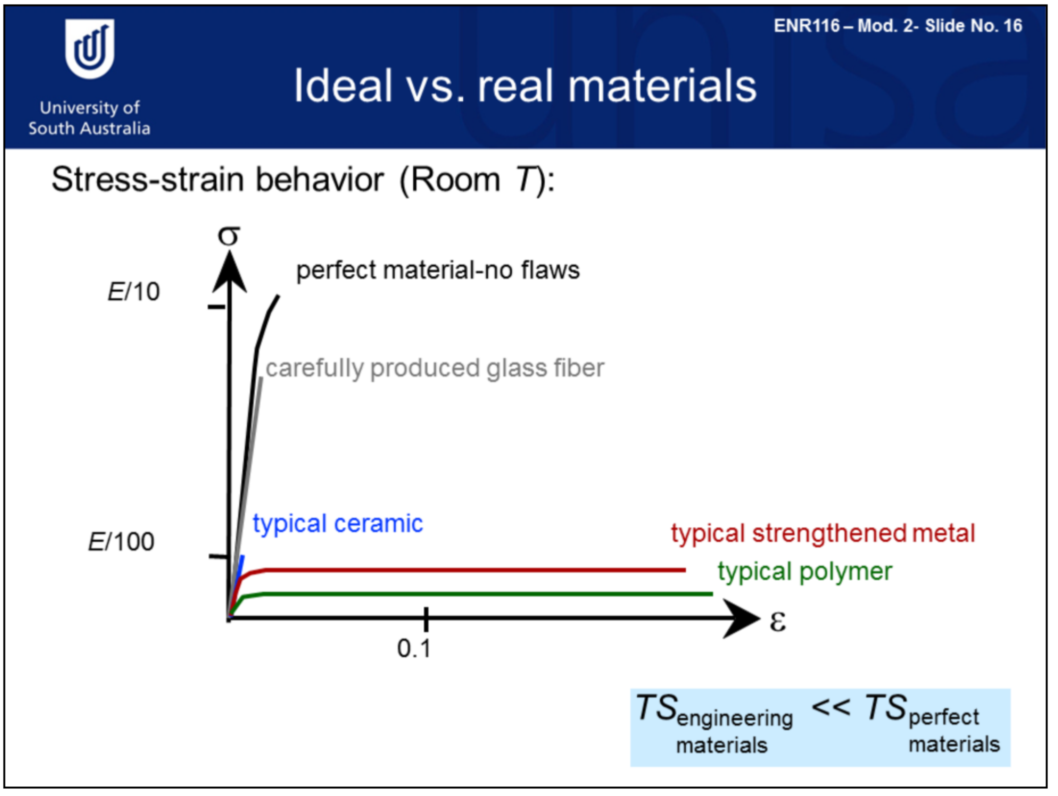
Test yourself 3: failure mechanisms





If you look at these model stress strain curves, you can see that a theoretically perfect material with no flaws should be very stiff and exhibit next to no plastic deformation. When produced carefully a glass fibre can begin to reach these material properties. However most engineering materials, ceramics, metals and polymers exhibit material properties vastly different to the material properties expected for a perfect material. This would suggest that a perfect material would result in an imperfect world as perfect materials would fail in a sudden and catastrophic manner. Material scientists and engineers spend a lot of time carefully designing in impurities into materials to affect their behaviour at failure. It is normally preferred that a material fails in a ductile manner, showing lots of plastic deformation and giving plenty of warning rather than suddenly and with no warning.

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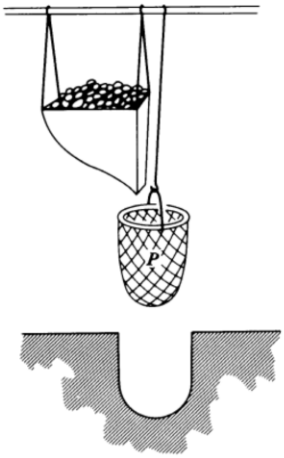
Ideal vs. real materials

da Vinci (500 yrs ago!) observed...

The longer the wire, the smaller the load for failure.



Reason:

Flaws cause premature failure

This discrepancy is not a new discovery. Leonardo da Vinci observed that the longer the wire the smaller the load needed for failure to occur. This is because it is the flaws in the material that cause the premature failure of the material.

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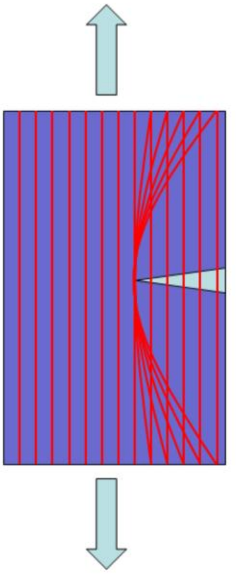
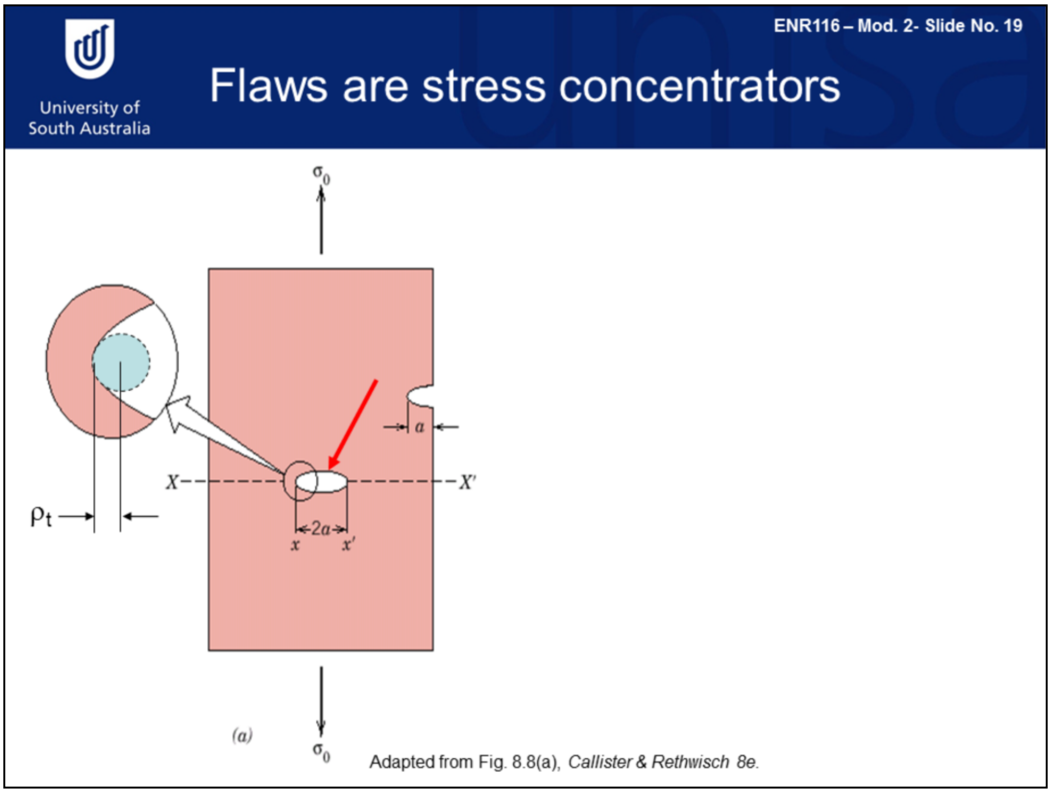
Stress concentrators

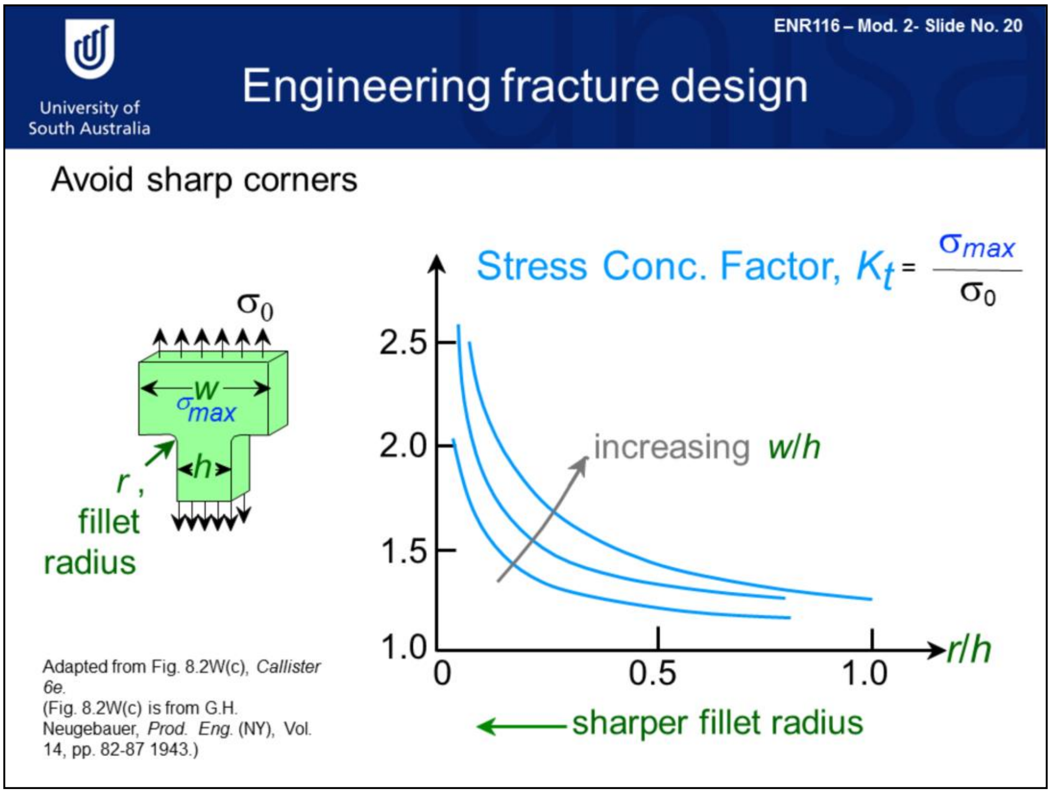


http://www.open.ac.uk/openlearn/science-maths-technology/engineering-and-technology/structural-integrity-materials-testing?track=2

Whilst necking of a sample can act as a stress concentrator, on a smaller scale it is the flaws in the material that act as the stress concentrators. If we imagine this to be a block of material under tensile load. If we then introduce a crack into the material the stresses in the bulk material travel in a straight line. However the stresses in the cracked area, cannot jump the crack, there is a gap. They are therefore forced around the crack and because they still ideally want to travel in a straight line they end up becoming concentrated around the crack tip. If you have the time, please look at this video provided by the Open University in the United Kingdom. This looks at another way of looking at the stresses within materials.

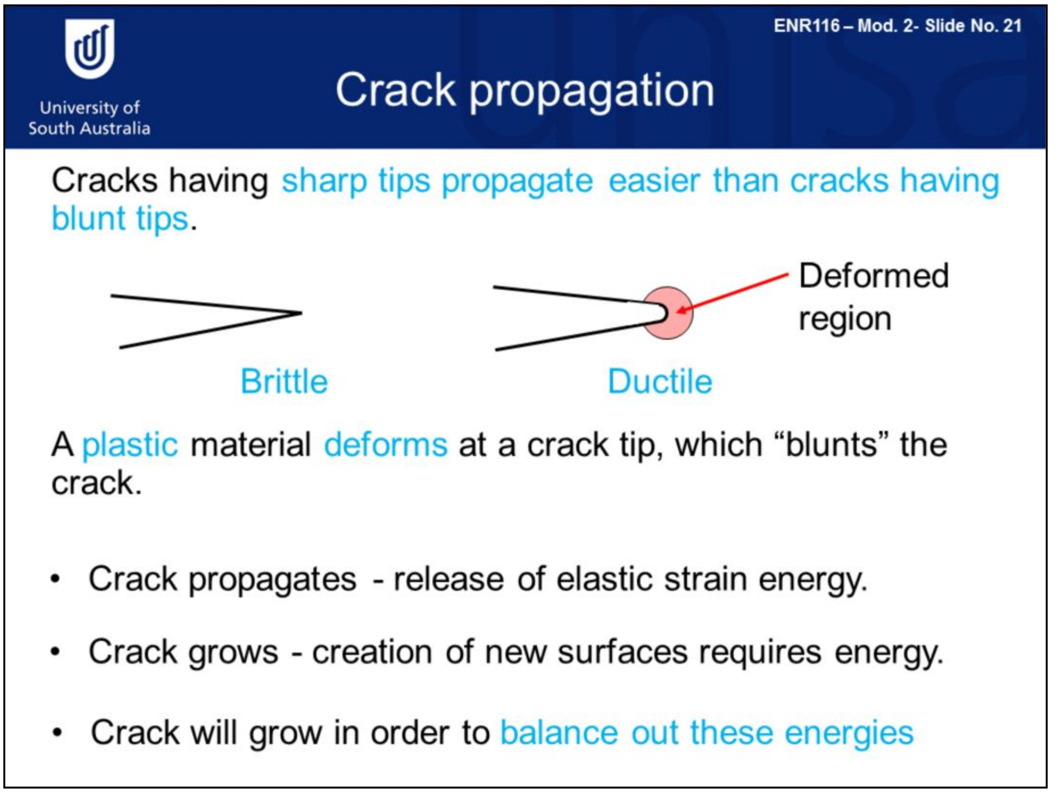


If we assume that the crack is an elliptical hole within the material then the maximum stress at the crack tip or sigma m can be approximated using the equation sigma m equals 2 times the applied nominal tensile stress multiplied by a divided by rho t. a is the length of a surface crack or half the length of an internal crack and rho t is the radius of curvature of the crack tip. A over rho t is raised to the power of one half. Sigma m is also equal to Kt, or the stress concentration factor multiplied by the nominal applied stress. So rho t is the radius of curvature, sigma o is the nominal applied stress and sigma m is the stress at the crack tip.



By understanding that stresses are concentrated at corners, and that the magnitude of this concentration is a function of the radius of curvature of the crack tip, designers can attempt to improve designs.

By avoiding sudden contour changes which result in sharp corners the stresses around these corners can be reduced. Round fillets with a large radius reduces the magnitude of the stress concentration factor where sharper fillets results in a larger stress concentration factor.



Bearing this in mind it is logical that cracks that have a sharp tip propagate through a material easier than those with a blunt tip.

A crack propagating through a plastic material has a blunter tip than a crack propagating through a brittle material.

This is because the material plastically deforms at the tip of the crack blunting it. The crack therefore has to work harder to propagate through the material.

Griffith proposed a theory of crack growth in brittle materials whereby during the propagation of a crack there is a release of elastic strain energy, this is some of the energy stored in the material as it elastically deforms.

Additionally during the growth of a crack new surfaces are created within the material which increases the surface energy of the system. A crack will grow in order to balance out these energies.

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Criterion for crack propagation

Crack propagates if crack-tip stress (σ_m) exceeds a critical stress (σ_c)

For ductile materials => replace γ_s with $\gamma_s + \gamma_p$ where γ_p is plastic deformation energy.

Griffith described the conditions for crack growth in terms of a critical stress required for crack propagation or sigma c.

For brittle materials this is equal to twice the material elastic modulus multiplied by the specific surface energy, gamma s, divided by pi times one half the length of an internal crack. This is then raised to the power of one half. For ductile materials crack extension involves more than increasing the surface energy of the material. Therefore the unit of specific surface energy is changed and becomes the specific surface energy plus the plastic deformation energy, gamma p.

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Design against crack growth

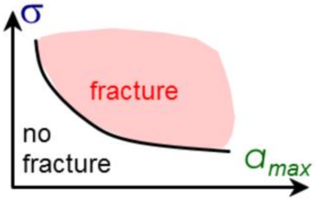
Crack growth condition:

$$K \geq \quad = \quad \sqrt{\pi}$$

Largest, most highly stressed cracks grow first.

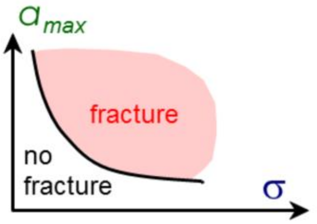
--Scenario 1: Max. flaw size dictates design stress.

$$\sigma_{design} < \frac{K_c}{Y\sqrt{\pi a_{max}}}$$

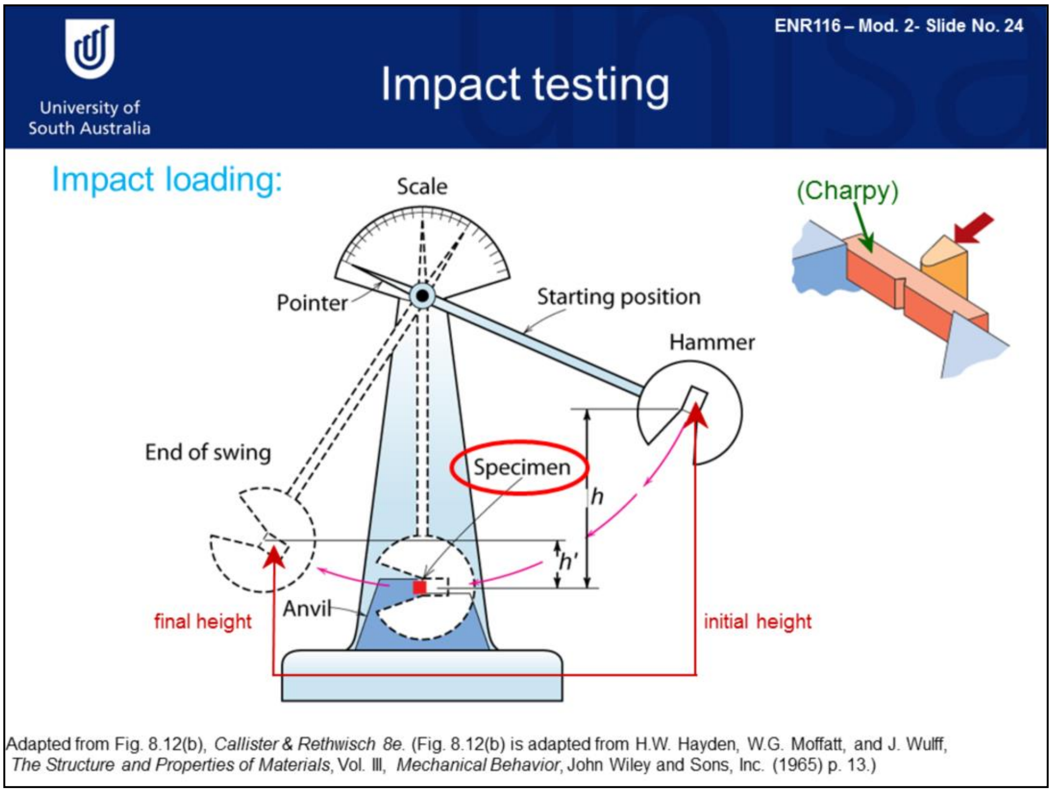


--Scenario 2: Design stress dictates max. flaw size.

$$a_{max} < \frac{1}{\pi}\left(\frac{K_c}{Y\sigma_{design}}\right)^2$$



When designing against crack growth it is useful to understand the material fracture toughness or Kc. This is a relationship whereby the critical stress for crack propagation is multiplied by Y. Whereby Y is a dimensionless parameter that depends on the crack and specimen sizes and geometries as well as the manner of the applied load. It is normally around 1. So sigma c multiplied Y is then multiplied by the square root of pi multiplied by a where a is the crack length. K_{IC}, where one is the Roman numeral one is the most commonly cited. This when the applied stress is a tensile stress. K_{IIC} is where the applied force is a sliding force and K_{IIIC} is where the applied stress is a tearing stress. The largest and most highly stressed cracks grow first, so you design around this by either calculating your maximum flaw size and using that to design the stresses experienced by the material or you design the stresses to dictate the maximum acceptable flaw size. Ultimately the important thing is that the material and component don’t fail.

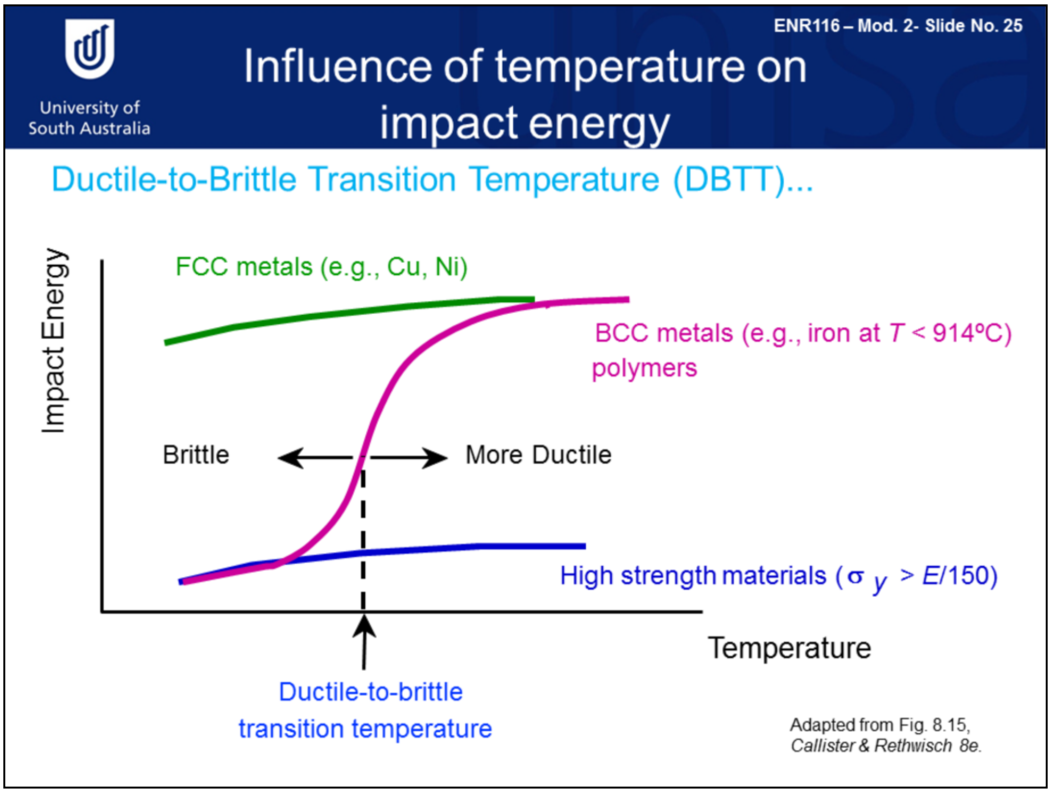


A number of methods are used to measure the fracture toughness of a material.

Impact testing is one of the most common methods of doing this of which the Charpy impact test is the most commonly used.

In this test the sample of material which has a square cross section has a V shaped notch machined into it. This is then mounted in the test machine and a pendulum is dropped from a known height. The pendulum then breaks the material loosing energy in the process. As a result of loosing this energy it does not reach the same height at the end of the swing that it started at. The difference between the starting height and final height is used to calculate the energy needed to fracture the material.

A brittle material will require less energy expenditure than a ductile material. If the testing is made more extreme for example by reducing the temperature, other material properties such as the ductile to brittle transition can be investigated.



It can be seen here that some materials, such as face centred cubic metals show no ductile to brittle transition. Others such as body centred cubic metals like iron which has a ductile to brittle transition at 914 degrees centigrade show a definite ductile to brittle transition. This is shown by plotting a graph of impact energy from a test like the Charpy impact test against temperature.

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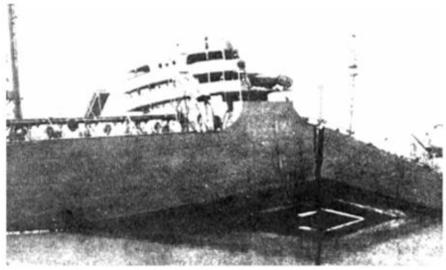
Design strategy: Stay above the DBTT

Pre-WWII: The Titanic

Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic*.)

WWII: Liberty ships



Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

Problem: Steels were used having DBTT's just below R_T

The best design strategy is to be aware that metals can exhibit a ductile to brittle transition and to stay above this by selecting your material carefully. Here are two rather famous examples of ships failing in part due to incorrect material selection. For the liberty ships bad design was also at fault. This is because not only was the wrong welding material selected so that when the ships were going through the North Sea in the middle of winter it passed through its ductile to brittle transition and became brittle. The liberty ships were built quickly in 2 halves which were then welded together. As the welding material became brittle cracks started to form and because there were no corners to stop them propagating they propagated around the circumference of the hull.

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Summary

- Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
- Sharp corners produce large stress concentrations and premature failure.

So in summary, flaws act as stress concentrators that cause failure at stresses lower than the calculated theoretical values. Sharp corners produce larger stress concentrations and therefore premature failure. This is another reason that ships don’t have proper windows and doors. They have port holes and oval doors instead. This is because the whole of the fabric of a ship is constantly experiencing flexural stresses and sharp corners would just cause the metal to fail.

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Thank you

Thank you for your attention during this lecture summary. The concepts covered in this lecture summary are covered in chapter eight of the course textbook along with the textbook online resources. If you have any questions please post them on the message board.