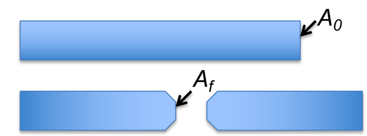
Ch.6.4

Properties Obtained from the Tensile Test (Part 2)

- Ductility: Ability of a material to be permanently deformed without breaking when a force is applied.
- Does copper used for wire have high or low ductility?
- Ductility can be quantified using tensile testing:
  - % Elongation
  - % Reduction in Area



1. Measure original gauge length or cross-sectional area of sample
2. Measure length or cross-sectional area **after** the specimen breaks

$$\% \text{ elongation} = \frac{l_f - l_0}{l_0} \times 100$$

$$\% \text{ reduction in area} = \frac{A_0 - A_f}{A_0} \times 100$$

(Note: "after" values l_f, A_f do not include elastic deformation which disappears when the sample breaks)

Effect of Temperature

- Temperature can significantly affect many of the mechanical properties discussed

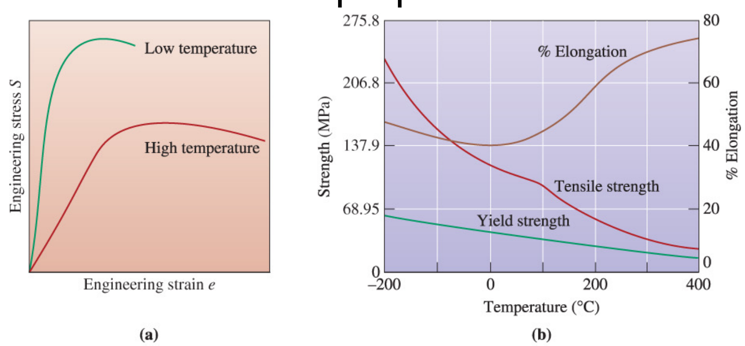


Figure 6-11 The effect of temperature (a) on the stress strain curve and (b) on the tensile properties of an aluminum alloy.

For higher temperature:
- Most properties decrease (yield strength, UTS, *E*)
- Ductility increases

- What does yield strength correspond to?
  - Stress at which plastic deformation starts
- How can we control yield strength (slip)?
  - Control dislocation motion via:
    1. Other dislocations (strain hardening)
    2. Grain size (grain strengthening)
    3. Point defects (solid-solution strengthening)
- Why does the yield strength ↓ at higher temperatures?

1. Typically have a decreased dislocation density
   - Energy assists formation of ideal crystal structure
   - Dislocations don't interfere with each other
2. Increase in grain size via grain growth
   - "Recrystallization" – discussed in Ch.8
3. Strengthening due to ultra-fine particles may decrease
   - These precipitates grow in size

Ch.6.5

True Stress and True Strain

- We have been using: $S = \frac{F}{A_0} \quad e = \frac{\Delta l}{l_0}$
- Since the dimensions of the specimen used to calculate engineering stress are changing when a material is deforming, we can define a more accurate:

$$\text{True stress} = \sigma = \frac{F}{A} \qquad \text{True strain} = \varepsilon = \int_{l_0}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) = \ln\left(\frac{A_0}{A}\right)$$

- Important: these values are instantaneous
  - Depend on *A* and *l* of specimen at a particular time
- We can also convert between engineering and true stress and strain via:

$$\sigma = S(1+e) \qquad \varepsilon = \ln(1+e)$$

(Not valid beyond onset of necking – see derivation on pg.197)

Shape of True stress-strain curve differs:
- Same as Engineering stress-strain up until yield point
- No maximum in true stress-strain curve
- True stress-strain curve typically truncated at UTS point
  - Why do we do this?

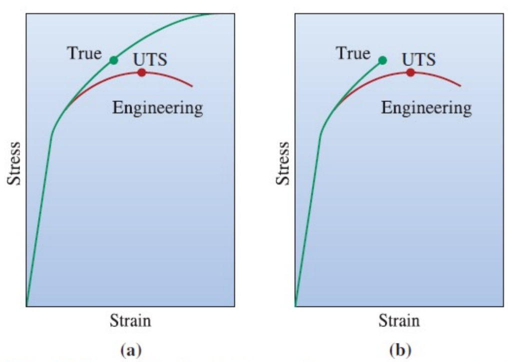


Figure 6-12 (a) The relation between the true stress–true strain diagram and engineering stress–engineering strain diagram. The curves are nominally identical to the yield point. The true stress corresponding to the ultimate tensile strength (UTS) is indicated by circles. (b) Typically true stress strain curves must be truncated at the true stress corresponding to the ultimate tensile strength, since the cross-sectional area at the neck is unknown.

Ch.6.6

Brittle Materials

- Ductile materials “neck” at the maximum stress (engineering stress-strain curve)
- <u>Brittle</u> alloys fail at the maximum load
  - Fracture strength = Tensile strength
- Very brittle materials (glasses, ceramics):
  - Fracture strength = Tensile strength = Yield strength

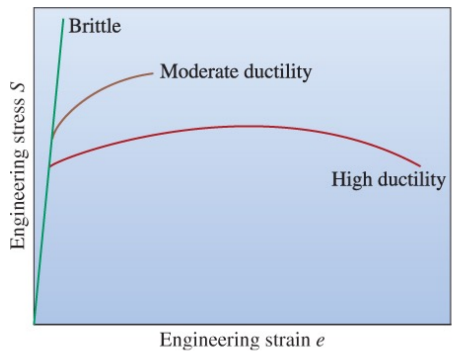


Figure 6-13 The engineering stress strain behavior of brittle materials compared with that of more ductile materials.

Ch.6.7

Hardness of Materials

- <u>Hardness test</u> is a measure of the resistance to penetration of the surface of a material by a hard indenter
  - Used for a qualitative measure of the properties of the material and can represent its resistance to scratching or indentation, wear and abrasion.
- Several types of standard tests exist:
  1. Brinell Hardness
  2. Rockwell Hardness
  3. Etc.

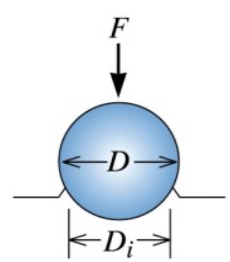
Brinell Hardness Test

- Hard steel sphere forced into surface of material
- Diameter of indentation impression is measured using a microscope
- Brinell hardness number BHN (or HB) is calculated from:

$$BHN = \frac{2F}{\left(\pi D\left[D - \sqrt{D^2 - D_i^2}\right]\right)}$$

Note: This method only measures the **plastic** deformation

F = applied load, kg
D = diameter of indenter, mm (typically ~10 mm)
D_i = diameter of impression (typically 2-6 mm)



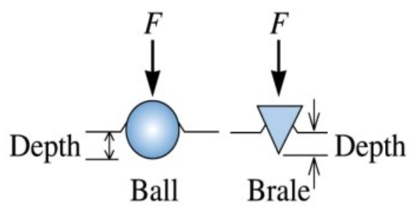
Brinell test

<u>For Steel only:</u> UTS (psi) = BHN x 500

“Video of Brinell hardness test”

6-7 Rockwell Hardness

- Indenter forced into surface of a material
- The depth of the impression under load is measured and converted to a dimensionless Rockwell hardness number (HR) by the testing machine
- Both elastic and plastic deformation measured (Why is elastic deformation also measured here?)

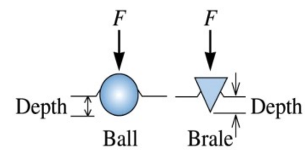


Rockwell test

- Different indenters and loads are used for different Rockwell scales in order to measure the hardness for a range of materials (see Table 6-5, pg. 203)
  - Small diameter steel ball for soft materials
  - Brale (a diamond cone) for hard materials
  - Loads typically ranging from 60 kg to 150 kg
  - Correspond to scales A, B, C, D, etc.

Harder material → larger hardness # e.g. HRC 55

- You perform a Rockwell hardness test on brass blocks in the lab



Rockwell test

Ch.6.9

Strain Rate Effects and Impact Behavior

- Materials may behave in a more brittle fashion if subjected to rapid impacts
  - High "strain rates"
  - E.g. silly putty
  - Why might a metal/alloy be more brittle for impacts? Insufficient time for slip to occur
- Impact test: used to evaluate brittleness of a material under impact loading
  - Material is strained at a much higher rate than tensile test:
    - Tensile testing: 0.001 s^{-1}
    - Impact testing: 1000 s^{-1}

Case Study: Columbia Space Shuttle Disaster

- Fuel tank covered by foam insulation
- Pieces of foam known to dislodge during launch and strike wings of shuttle
- Wings: Al, covered with thermal tiles to protect them from extreme heat during re-entry
- Jan.16, 2003: Foam struck leading edge of left wing during launch, creating a hole in tile (estimated ~10 in)
- Feb.1, 2003: On re-entry, superheated air penetrated hole and melted Al, eventually causing shuttle to break apart

BBC

Case Study: Columbia Space Shuttle Disaster

- A technical & organizational failure
- During mission, NASA used a computer program ("Crater", developed in 1970s) to assess potential damage of any foam impacts
- Crater results: might be heavy denting of tiles, but unlikely to lead to excessive heating during re-entry
- Crater had been validated by tests
- But size of foam that struck wing was 400x larger than test samples used in validation impact tests
- Impact test later performed with similar piece of foam (1.67 lb), made a 16in x 17in hole in tile

Sciencephoto.com

New York Times

BBC

- Impact tests:
  - Quick, convenient and inexpensive way to compare different materials' resistance to impact loading
  - 2 tests used: Izod and Charpy tests
  - Measure a material's <u>impact toughness</u>: the ability to withstand an impact blow
  - If the sample is notched, they can also measure <u>fracture toughness</u>, which is the ability of a material containing flaws to withstand an applied load

Difference in potential energy
= **impact energy** absorbed by the specimen during failure
= pendulum mass x g x (h_0-h_f)

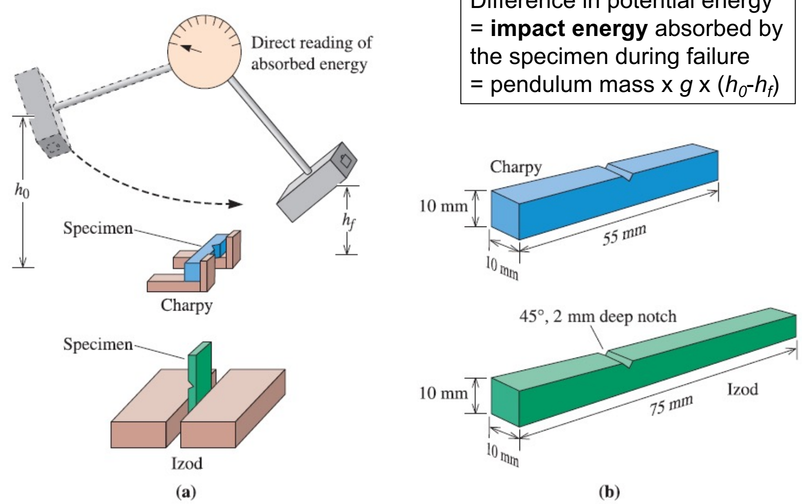
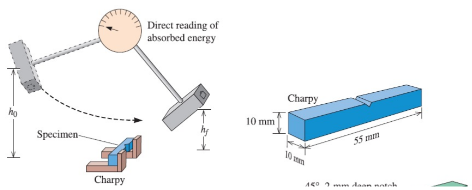


Figure 6-21 The impact test: (a) the Charpy and Izod tests, and (b) dimensions of typical specimens.

- Impact energy (J) measured by Charpy test
  = work done to fracture specimen
  = impact toughness
- Most work done in plastic deformation
  – Ductile materials ➔ higher impact toughness
  – How might impact toughness depend on temp?

Slip more difficult at lower temp. → brittle, lower impact toughness



- Why should we be interested in impact & fracture toughness?

- Very important for load bearing structures
- Need to know if material will survive the conditions that the structure will see in service
  - E.g. impacts at low temperatures: will the material fracture when notches/cracks present in the material?

Ch.6.10

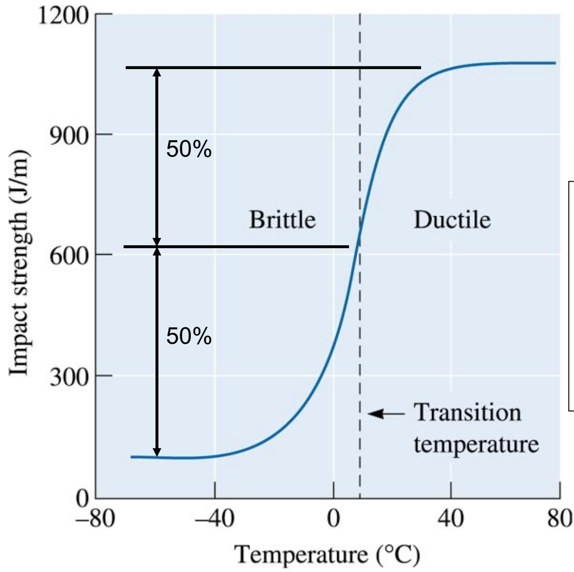
Properties Obtained from Impact Test

Ductile-to-Brittle Transition

- Many materials undergo a transition from ductile ➔ brittle behavior below a specific temperature
- Impact (Charpy and Izod) tests used to determine the ductile-to-brittle transition temperature (DBTT)
- Important to know DBTT:
  – Material will be subject to impacts during service
  – Require DBTT above or below operating temperatures?

Typically require DBTT < operating temperature

Figure 6.22 Results from a series of Izod impact tests for a tough nylon thermoplastic polymer.



1. Observe impact toughness as function of temperature
2. Can define transition, e.g., energy half-way between brittle and ductile regions

- Not all materials have a ductile to brittle transition:

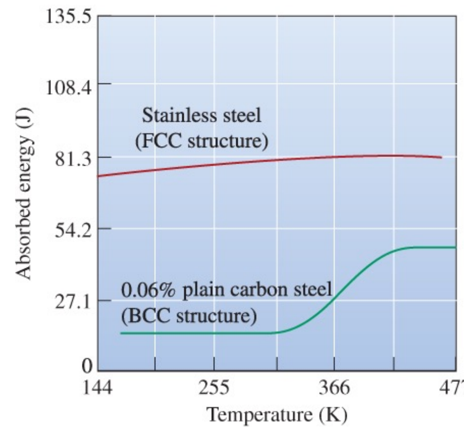
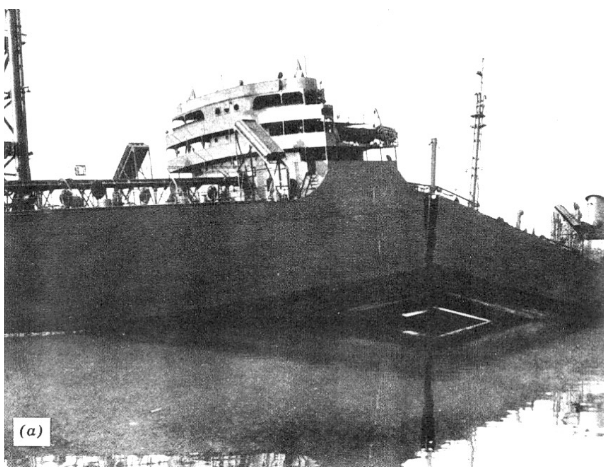


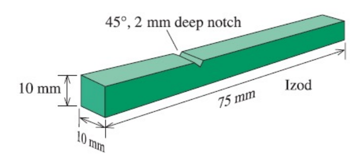
Figure 6-23 The Charpy V-notch properties for a BCC carbon steel and an FCC stainless steel. The FCC crystal structure typically leads to higher absorbed energies and no transition temperature.



Brittle Fracture of Steels

Fractured T-2 tanker S.S. Schenectady in 1941 and other such events ultimately led to the realization that steels can become like glass and fail by fast/brittle fracture at low temperatures and the invention of the Charpy Impact test.

Notch Sensitivity



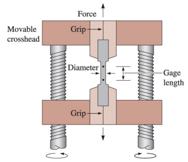
- From before:
  - If impact test sample is notched
  - Measure <u>fracture toughness</u> (ability of a material containing flaws to withstand an applied load)
- Notches caused by machining, fabrication, design or abrasion can reduce the toughness of a material
- Notch sensitivity can be evaluated by comparing absorbed energies (from impact tests) of notched vs. unnotched specimens
  - Absorbed energy lower if material is “notch-sensitive”

Ch.6

Chapter Summary & Material Selection

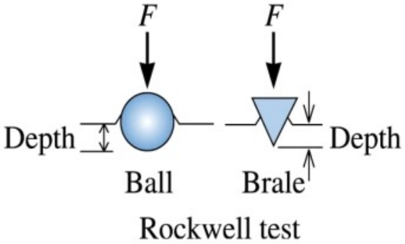
Summary

- The mechanical behavior of materials is described by their mechanical properties, which are measured by simple, idealized tests.
- These tests are designed to represent different loading conditions. Material properties reported in various handbooks are obtained from these tests.
- The tensile test describes material resistance to a slowly applied tensile stress. Important properties include yield strength, tensile strength, modulus of elasticity, % elongation & % reduction in area.



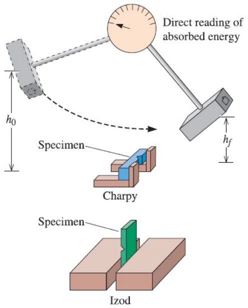
Summary

- The hardness test measures material resistance to penetration. It provides a measure of wear/abrasion resistance.
- A number of hardness tests (Rockwell, Brinell, etc.) are used. Hardness can often be correlated to other properties, particularly tensile strength.

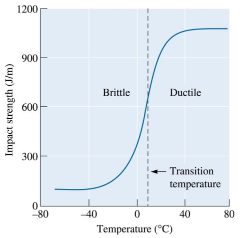


Summary

- The impact test describes a material's response to a rapidly applied load. Charpy and Izod tests are typical. The required energy for material fracture is measured and used as a comparison basis with other materials tested at similar conditions.

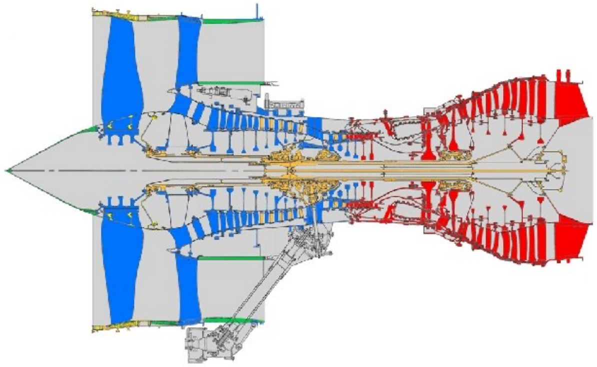


- Additionally, impact tests can determine a transition temperature above which a material fails in a ductile, rather than brittle, manner.



Materials Selection Based on Engineering Properties

- A designer needs first to define the required properties for each application before the most appropriate material can be selected:
  - Should it be stiff or strong or ductile or tough?
  - Will it be under constant load or cyclic loads?
  - Will it be subject to impact loading?
  - Should it be light weight?
  - Will it be exposed to corrosive environments or be subject to wear and abrasion?
  - Will it be exposed to high or low temperatures?



http://www.msm.cam.ac.uk/phase-trans/2003/Superalloys/coatings/index.html

Databases of Material Properties

- Databases covering a wide range of properties are available for a wide range of materials
- BUT…
  - Properties are usually determined in the laboratory under ideal conditions (may differ in practice)
  - Materials with the same nominal composition can have significantly different mechanical properties, depending on their microstructure
  - Changes in microstructure and the presence of defects introduced in processing (e.g. welding, riveting, cutting) can have major effects on the mechanical properties
- Therefore, use databases with care and be aware of their limitations!