Mechanical Behaviour of Materials

Chapter 04-2

Fracture: Morphology

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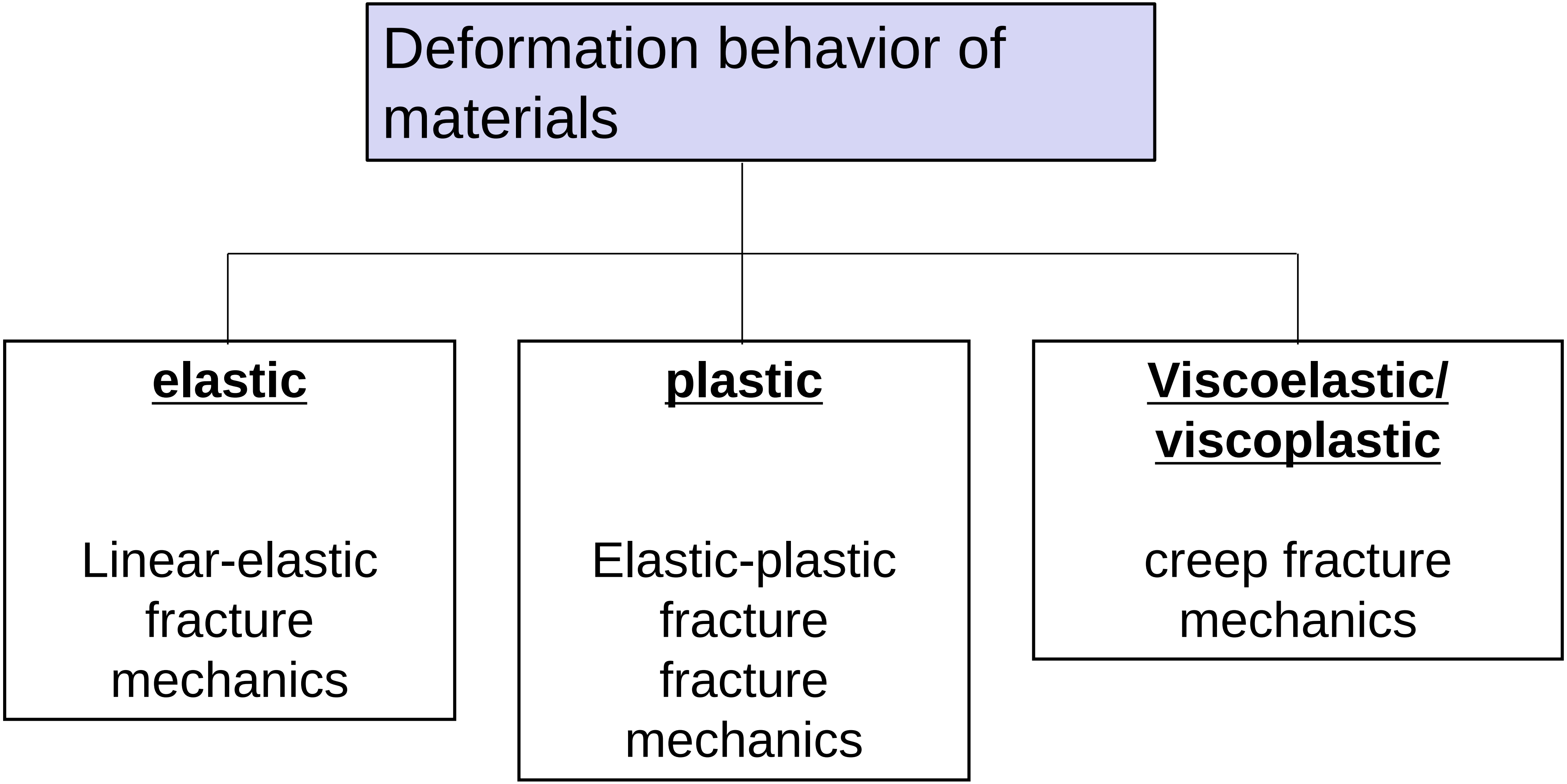
Example of fracture

Fig. 1.3 ICE railway accident near Eschede in 1998 as a result of a broken wheel rim

Classification of fracture processes:



Deformation behavior of materials

elastic

Linear-elastic fracture mechanics

plastic

Elastic-plastic fracture fracture mechanics

Viscoelastic/ viscoplastic

creep fracture mechanics

Cited from Meinhard Kuna, Finite Elements in Fracture Mechanics-Theory - Numerics - Applications, Springer, 2013.

Classification of fracture processes: conti.

Failure behavior of materials

brittle

cleavage fracture
rupture

ductile

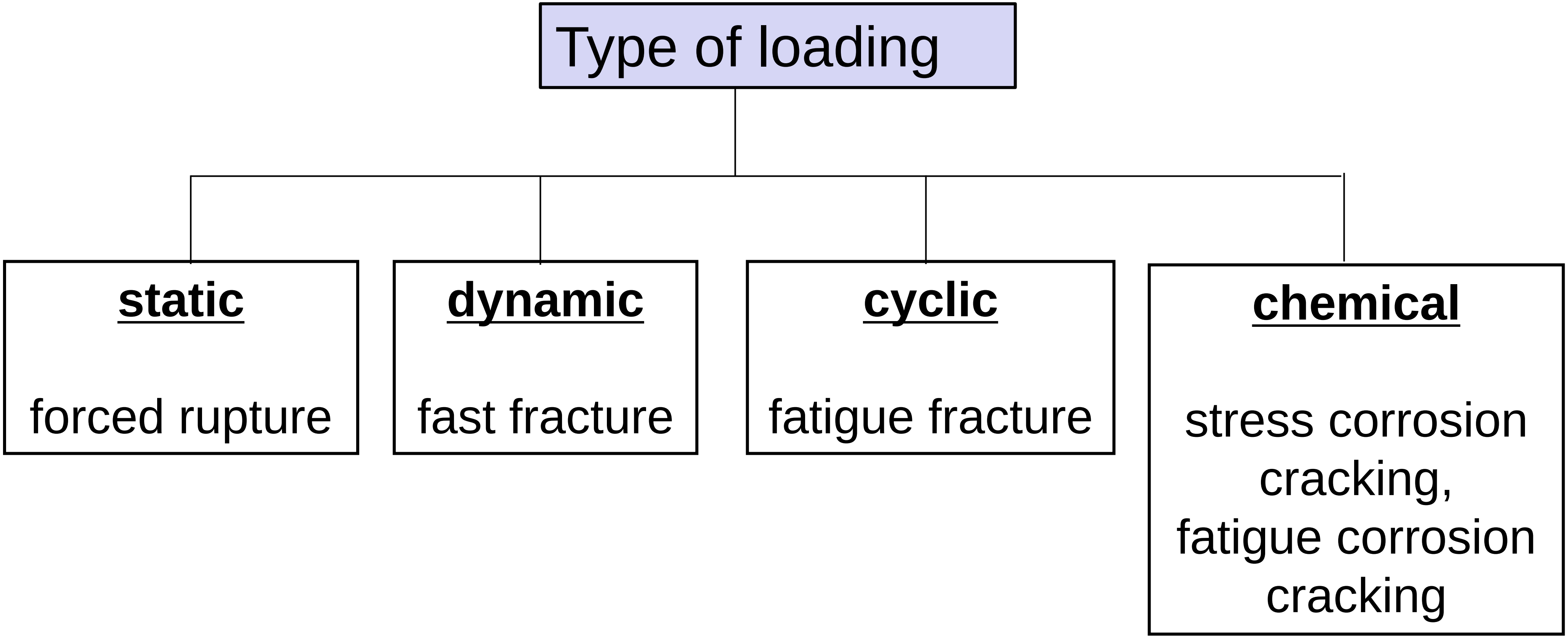
dimple fracture
shear fracture

creep

creep fracture
normal/shear fracture

Cited from Meinhard Kuna, Finite Elements in Fracture Mechanics-Theory - Numerics - Applications, Springer, 2013.

Classification of fracture processes: conti.



Type of loading

static

forced rupture

dynamic

fast fracture

cyclic

fatigue fracture

chemical

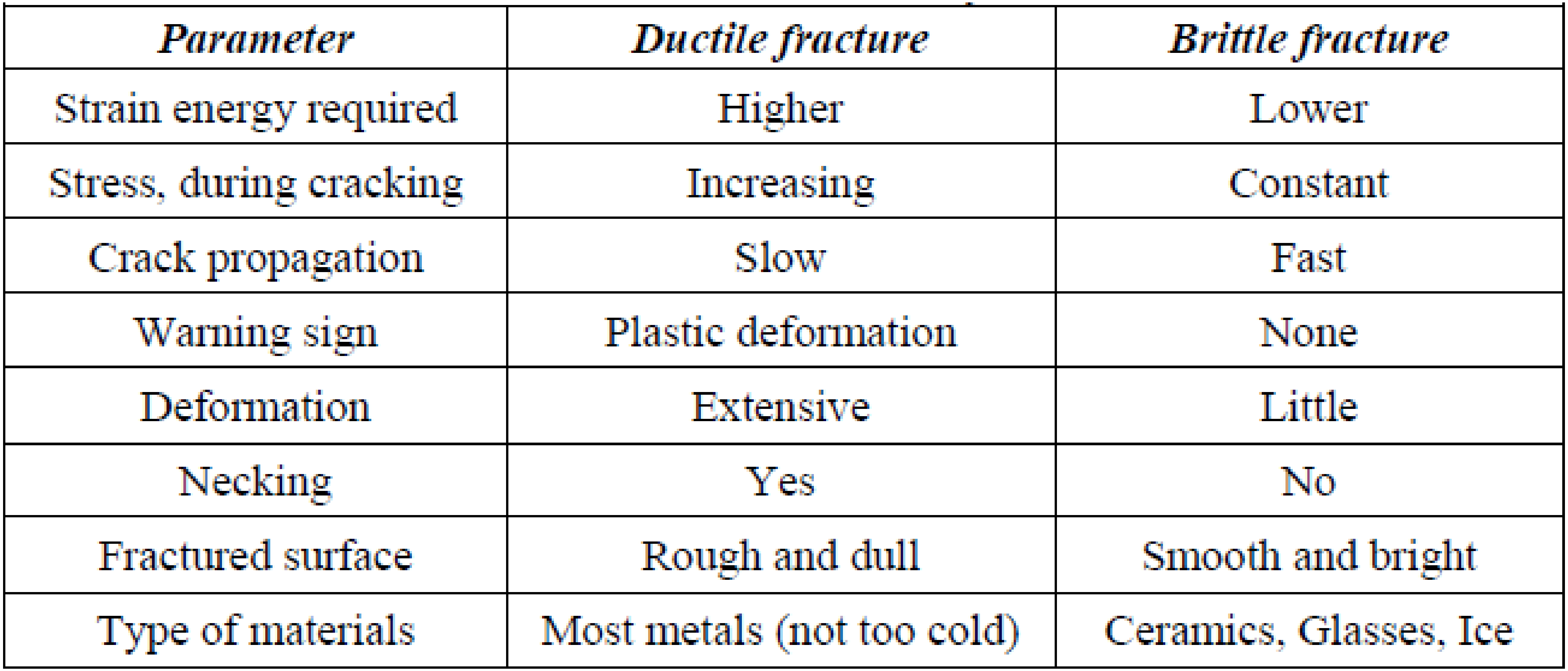
stress corrosion cracking, fatigue corrosion cracking

Cited from Meinhard Kuna, Finite Elements in Fracture Mechanics-Theory - Numerics - Applications, Springer, 2013.

Macroscopic Fracture Modes

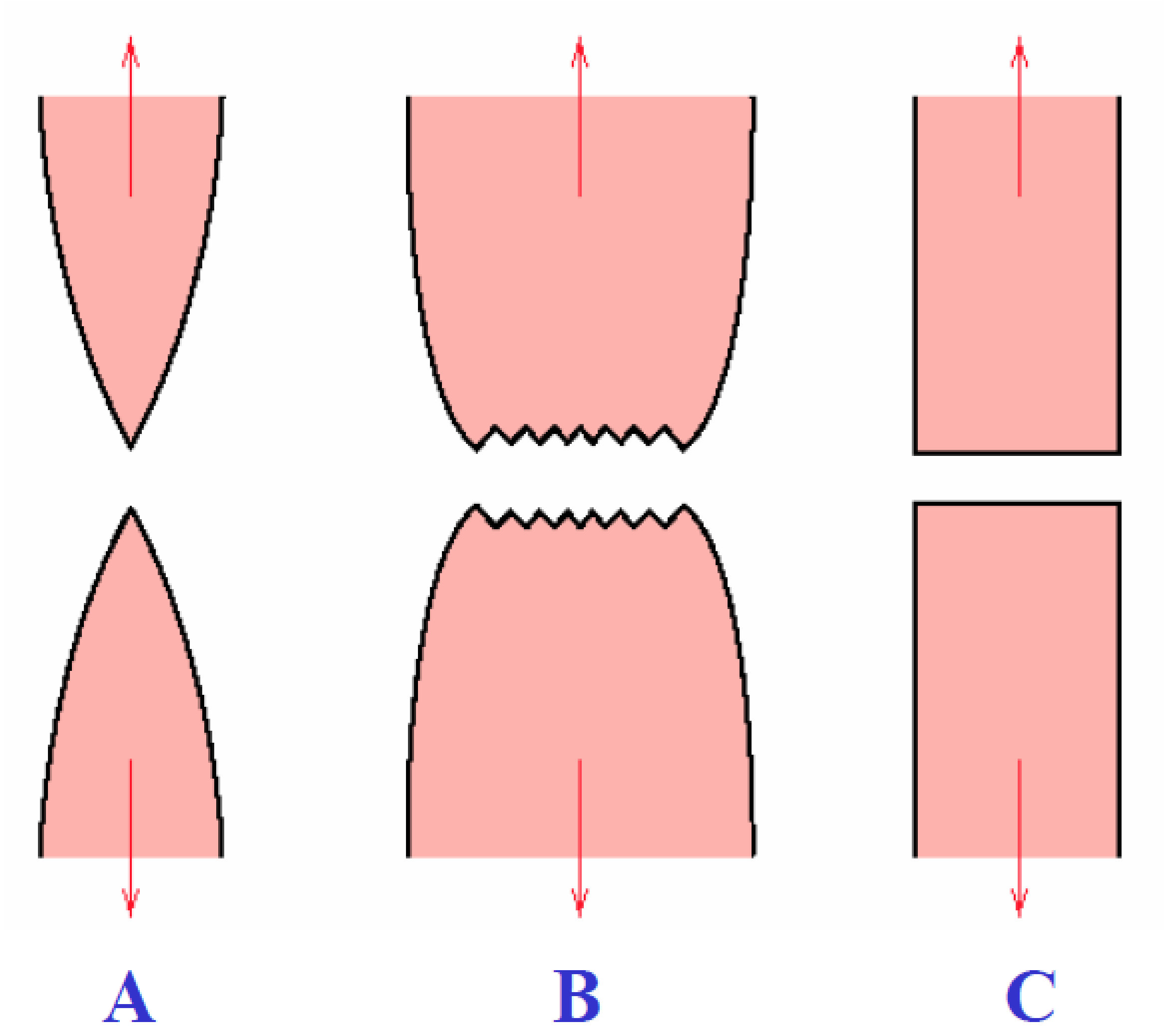
Characteristic	***Mode***	
Strain to fracture	Ductile	Brittle
Crystallographic mode	Shear	Cleavage (Normal stress)
Appearance	Fibrous and gray	Granular and bright
Crack propagation	Along grain boundaries	Through grains

Ductile and brittle fractures



Parameter	***Ductile fracture***	***Brittle fracture***
Strain energy required	Higher	Lower
Stress, during cracking	Increasing	Constant
Crack propagation	Slow	Fast
Warning sign	Plastic deformation	None
Deformation	Extensive	Little
Necking	Yes	No
Fractured surface	Rough and dull	Smooth and bright
Type of materials	Most metals (not too cold)	Ceramics, Glasses, Ice

Ductile and brittle fractures



A. Very ductile (rupture): soft metals, such as, Pb and Au at room temperature.

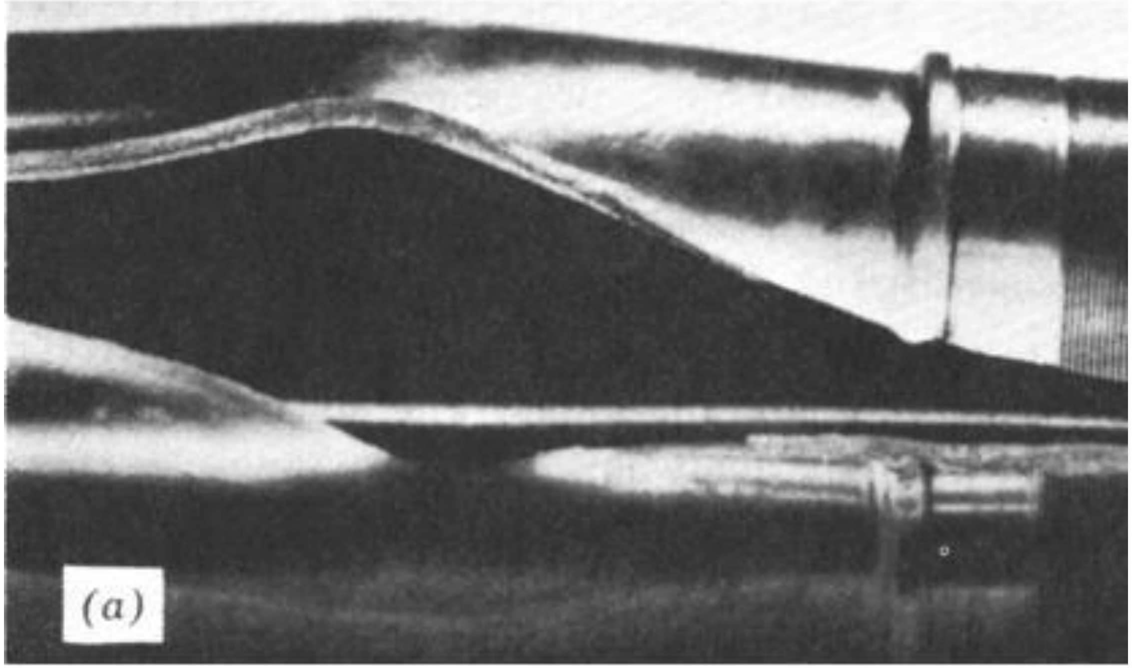
B. Moderately ductile:

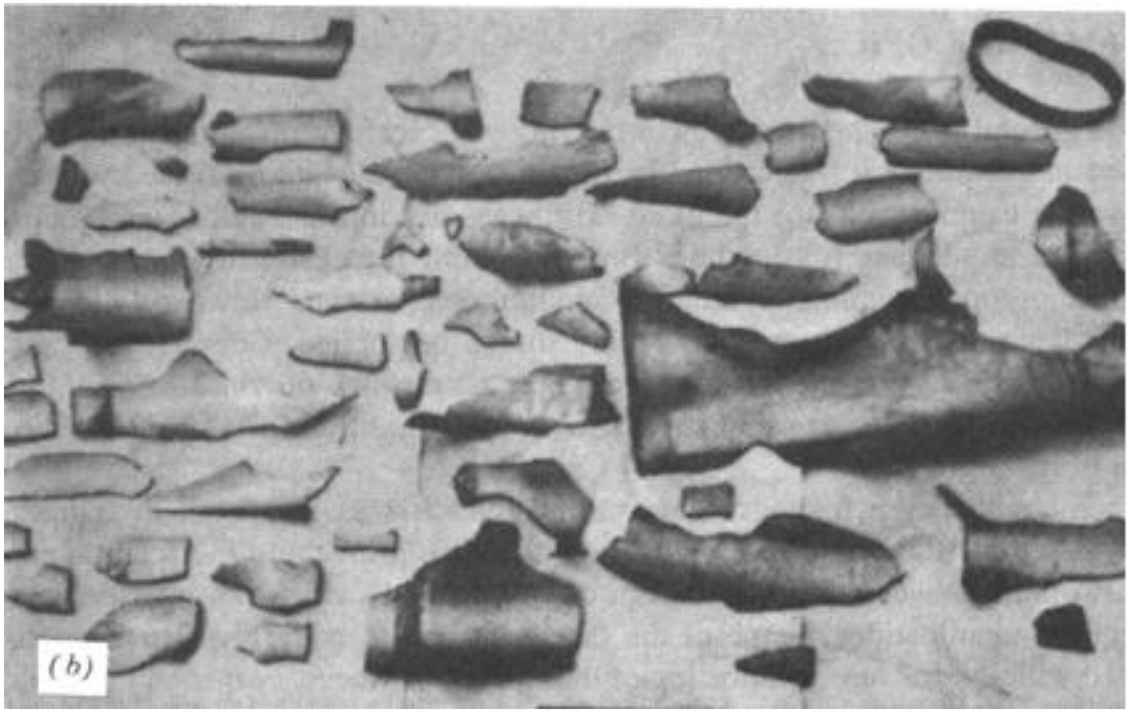
C. Brittle: ceramics

Examples of ductile and brittle fractures

- **Ductile failure:**
  --one piece
  --large deformation

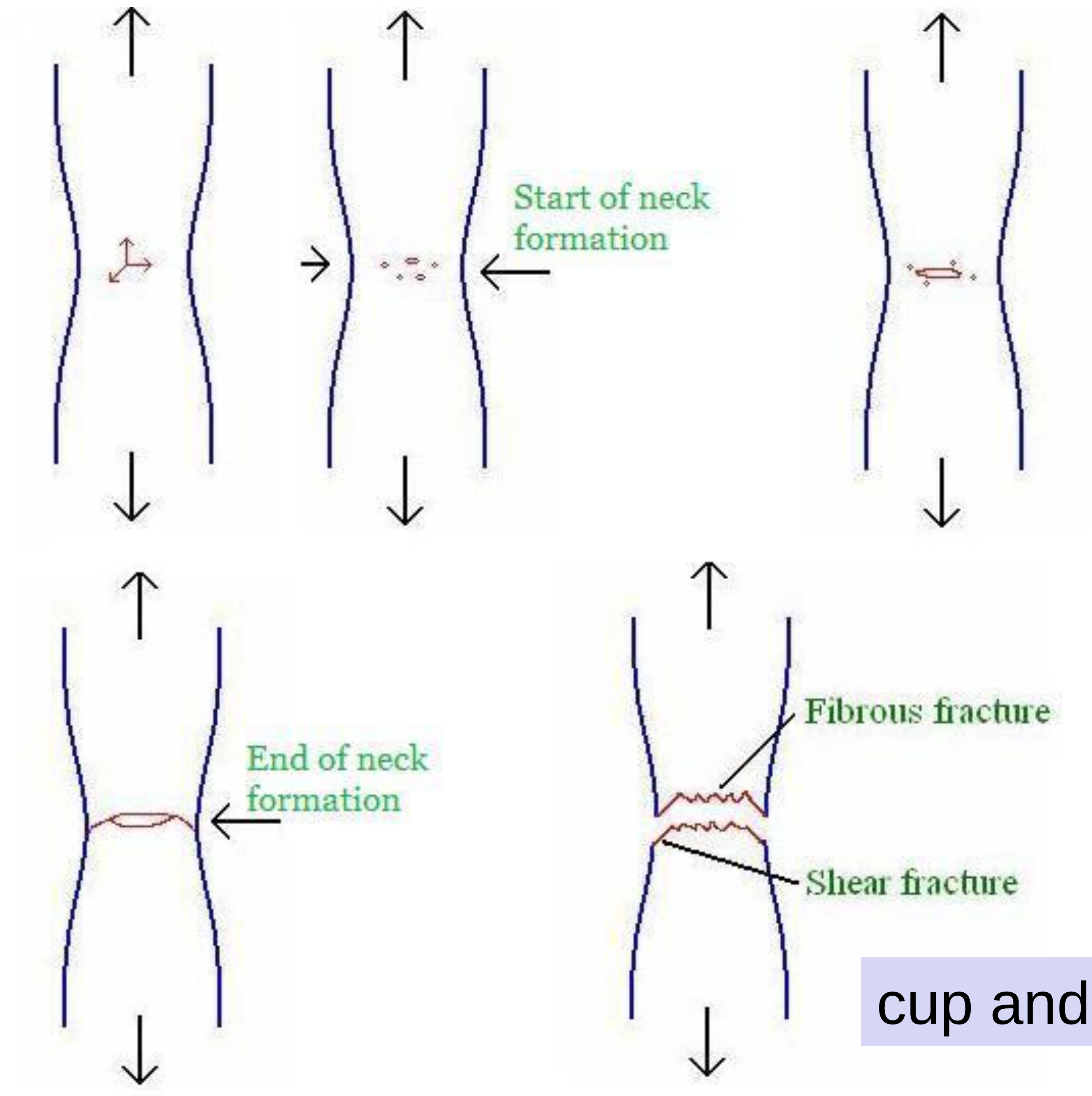
- **Brittle failure:**
  --many pieces
  --small deformation





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.

Stages of ductile fracture



1. The first formed micro-cracks and cavities grow large and finally join together to form a crack in the centre of the necked portion.

2. The cavity then spread in direction inclined at 45° to the tensile axis.

cup and cone appearance

Formation of microvoids

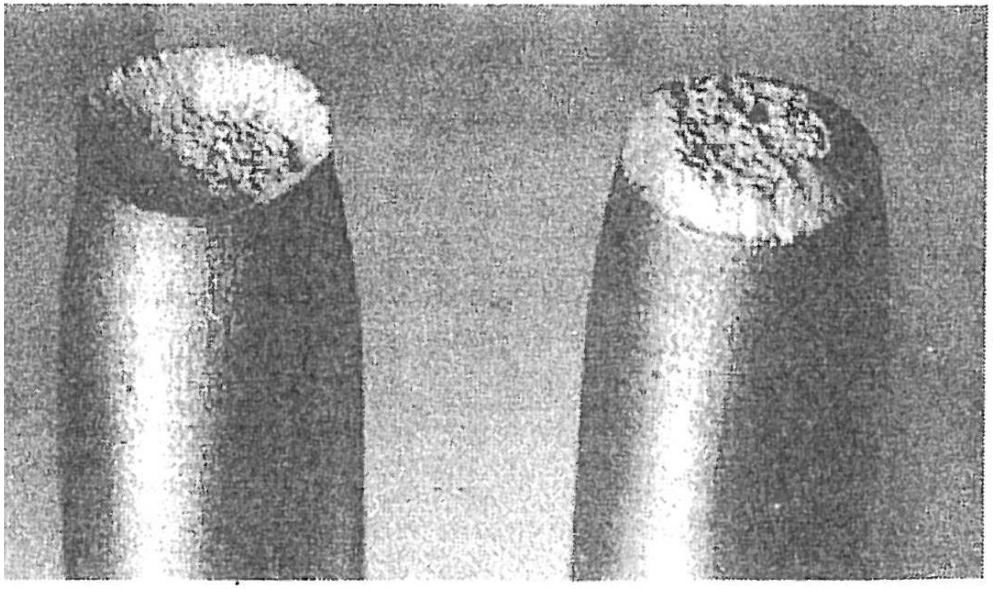
1. Most of the voids are formed at inclusions, precipitates and other second phases of ductile metal.

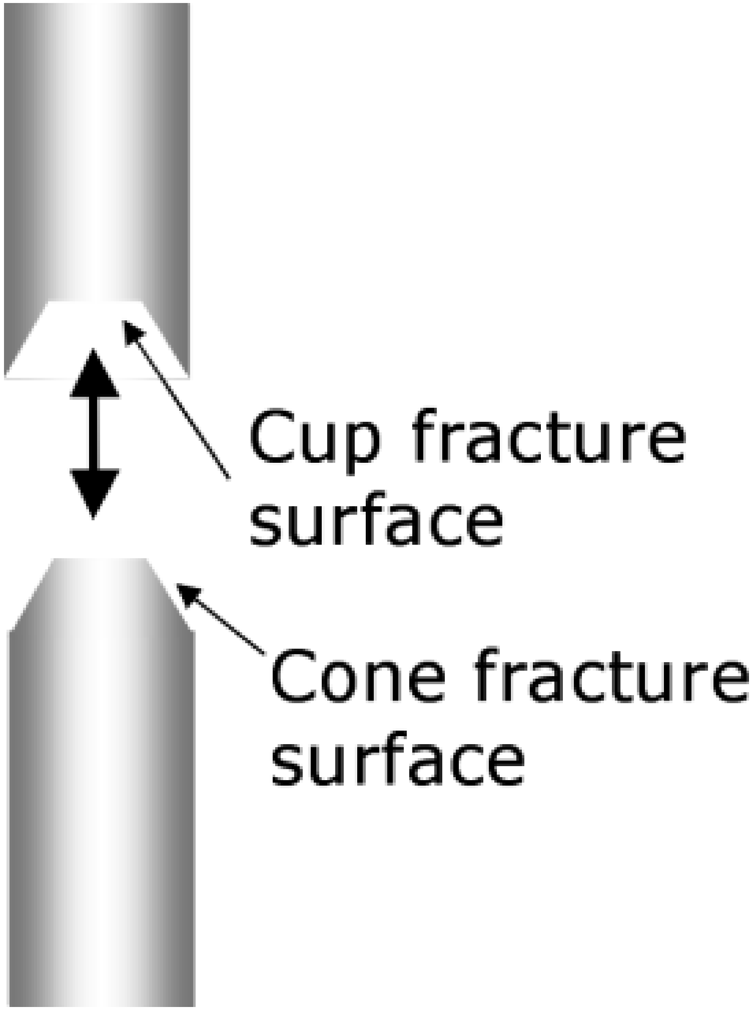
   Ballufi and Seigle have shown, however, that unless there exist cavity nuclei of reasonable size within a grain, the excess vacancy concentration generated during deformation probably never reaches a high enough value to form cavities homogeneously. One may speculate that in the observed regions of high dislocation density the material has exhausted its ability to work harden and in conjunction with the triaxial stresses at the crack tip, internal cracking or fracture occurs.

2. Voids can also nucleate at the intersection of slip bands at grain boundaries, twin boundaries and vacancy clusters

M.F. Horstemeyer, A.M. Gokhale, A void–crack nucleation model for ductile metals, International Journal of Solids and Structures, 36 (1999) 5029-5055.

Cup and cone fracture

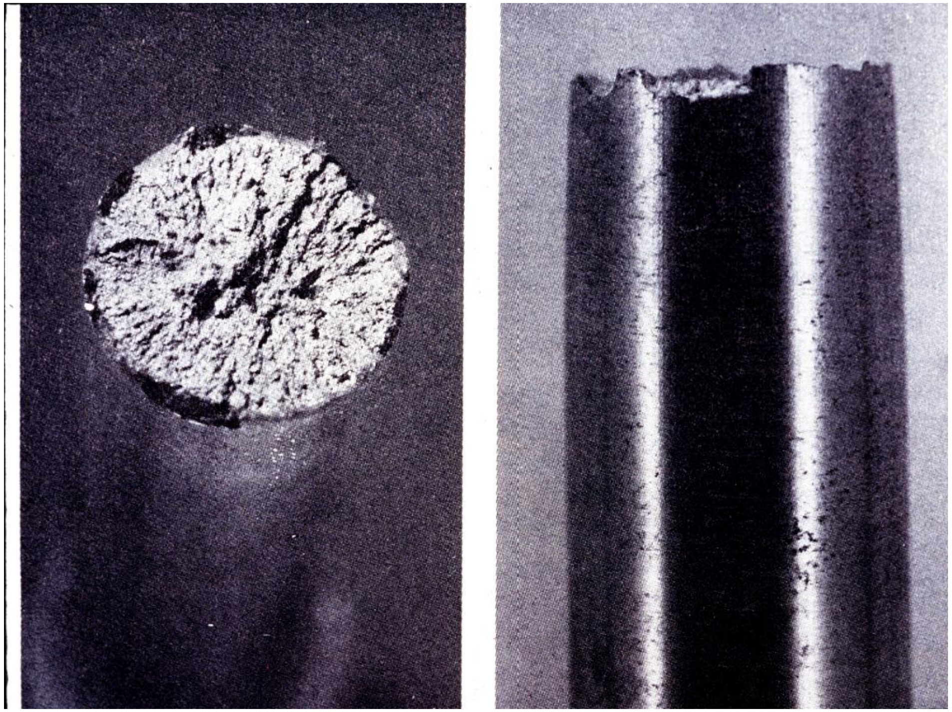




The size of the cup depends on the relative shear and cleavage strength values.

Metals with high yield strength give a smaller cup. The fracture faces are dull, irregular fibrous in appearance.

Macroscopic features of brittle fracture

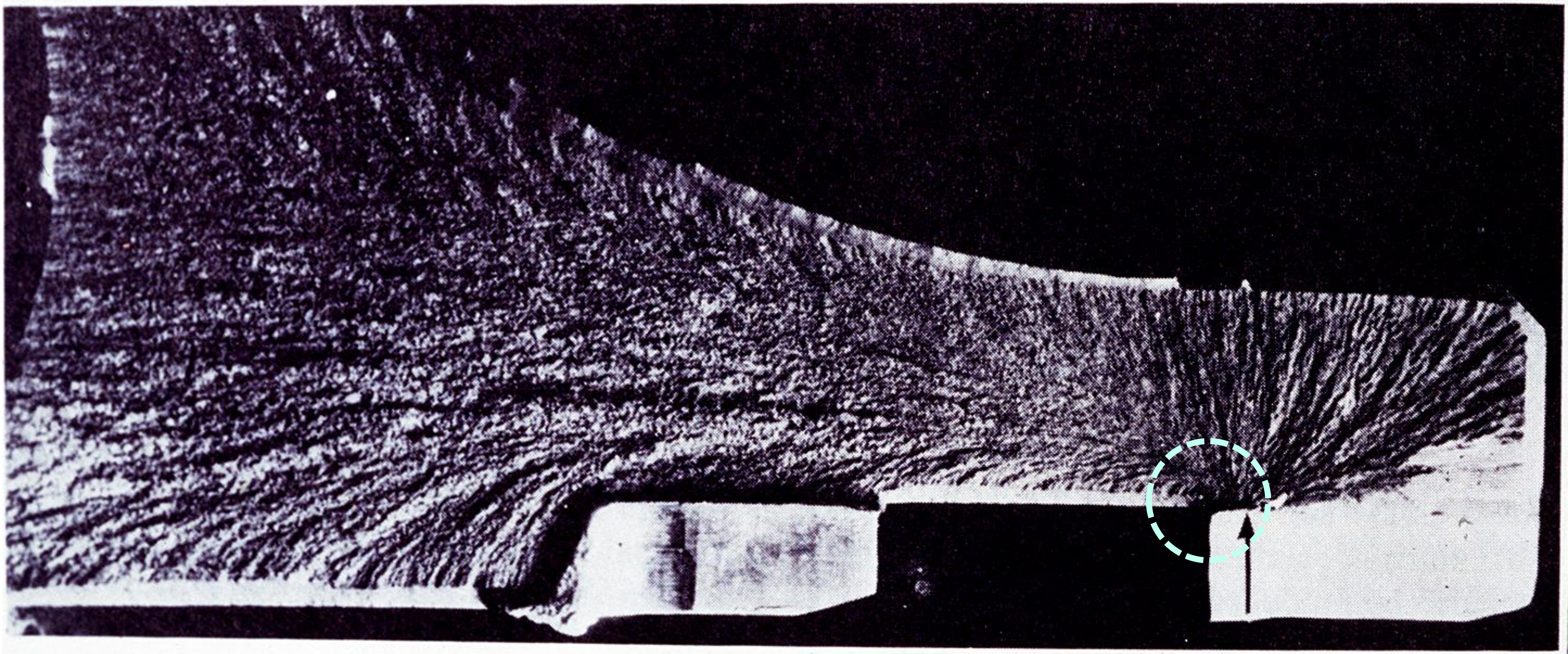


- Flat fracture face
- Little/No necking
- “Crystallized” fracture surface

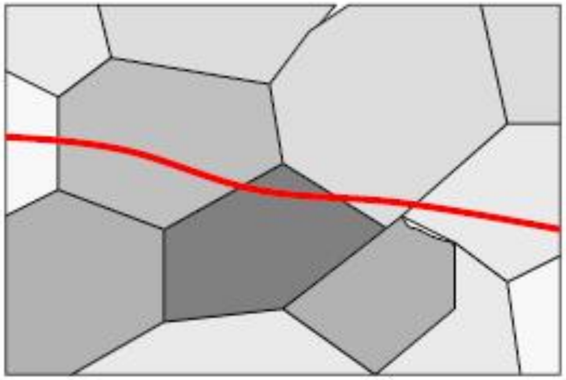
Macroscopic features of brittle fracture: conti.

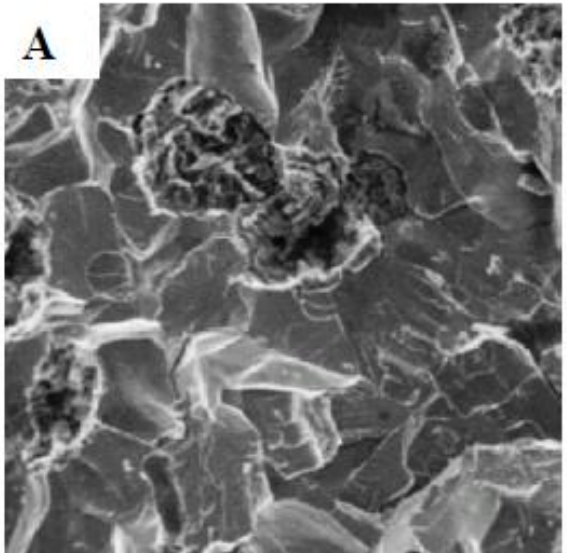
Fig. 9 Fracture surface exhibiting chevron pattern (left) pointing toward fracture origin, at a sharp corner

Fracture initiated at the location indicated by the arrow, where the corner of a snap-ring slot was specified to have a zero minimum radius. Fracture surface is that of a forging of AMS 6434 (vanadium-modified 4335) steel that was heat treated to a yield strength of 196 MPa (190 ksi).

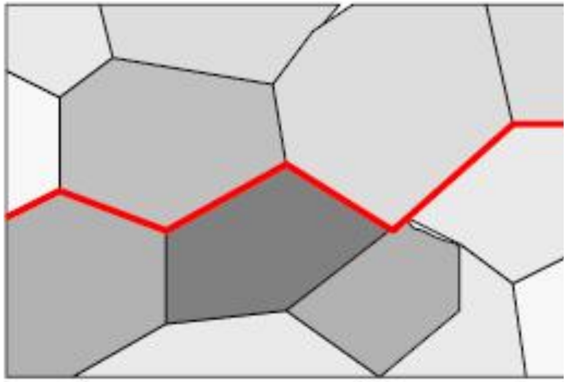


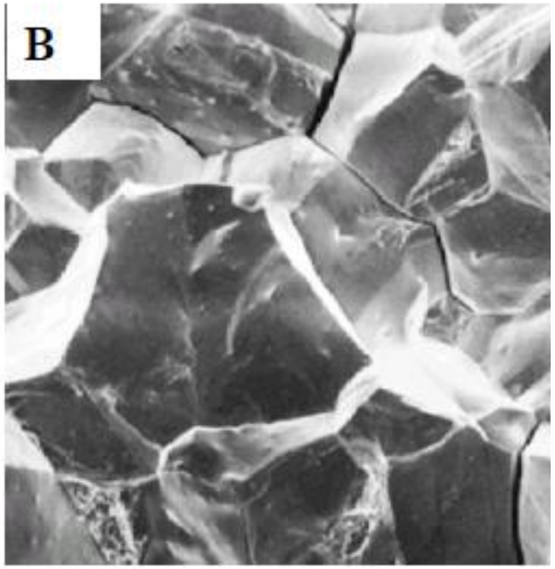
Microscopic features of brittle fracture:





A. **Transgranular fracture**: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.





B. **Intergranular fracture**: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)

Brittle fracture: Cleavage plane

Cleavage fracture occur on certain crystallographic planes (cleavage planes).

Cleavage occurs when the normal stress σ_n across the cleavage plane reaches a critical value σ_c .

Why?

$$\sigma_a = \frac{\sigma_c}{\cos^2 \phi} \qquad \sigma_n = \sigma_c$$

Applied stress

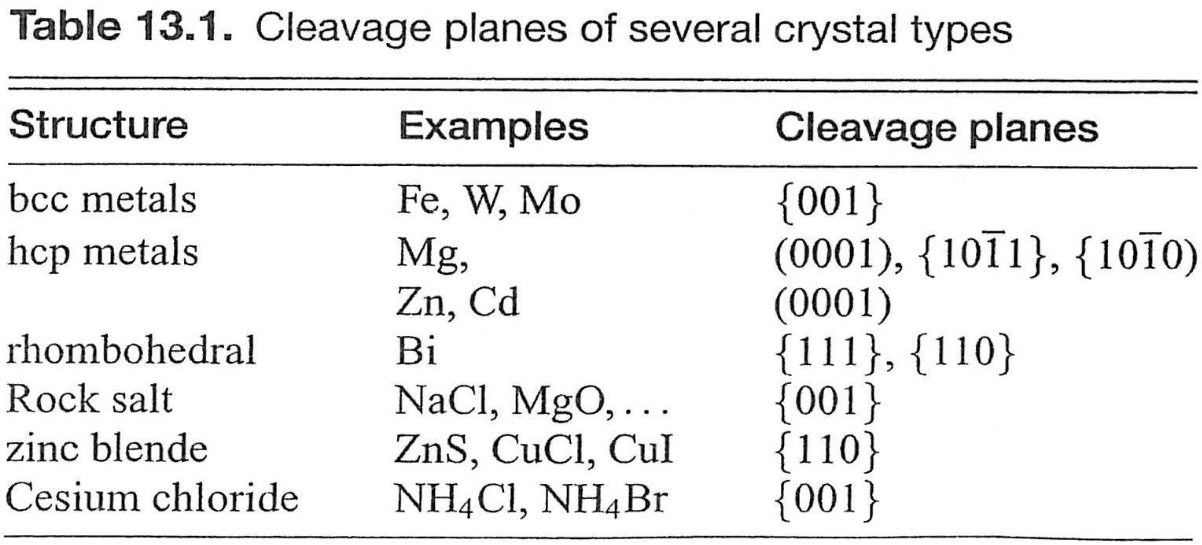


Table 13.1. Cleavage planes of several crystal types

Structure	Examples	Cleavage planes
bcc metals	Fe, W, Mo	$\{001\}$
hcp metals	Mg,	$(0001), \{10\bar{1}1\}, \{10\bar{1}0)$
	Zn, Cd	(0001)
rhombohedral	Bi	$\{111\}, \{110\}$
Rock salt	NaCl, MgO, . . .	$\{001\}$
zinc blende	ZnS, CuCl, CuI	$\{110\}$
Cesium chloride	NH_4Cl, NH_4Br	$\{001\}$

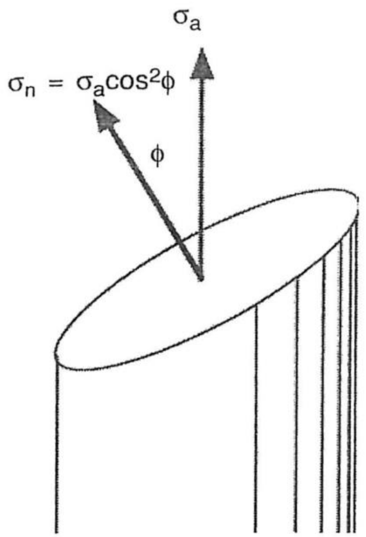
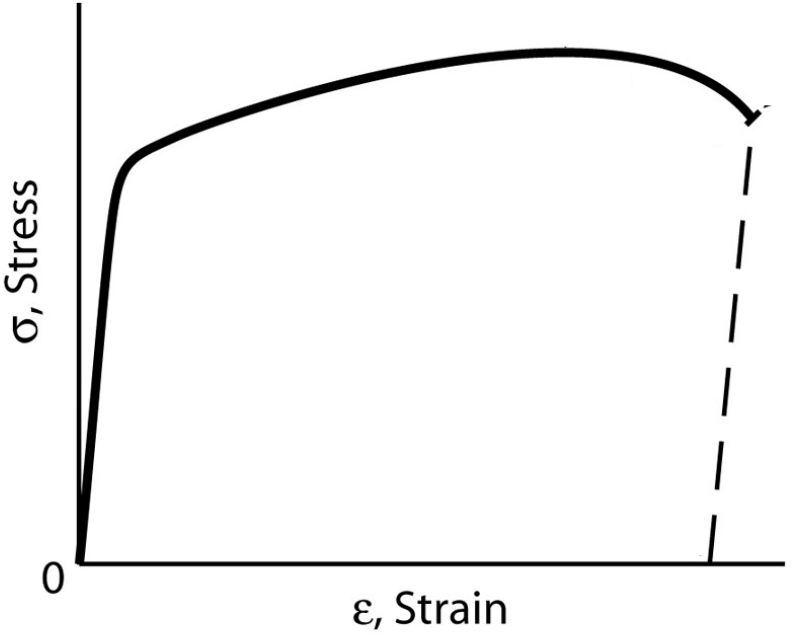


Figure 13.17. Cleavage plane and an applied stress. Cleavage occurs when the normal stress across the cleavage plane, $\sigma_n = \sigma_a \cos^2 \phi$, reaches a critical value, σ_c.

Measurement of toughness: tension test

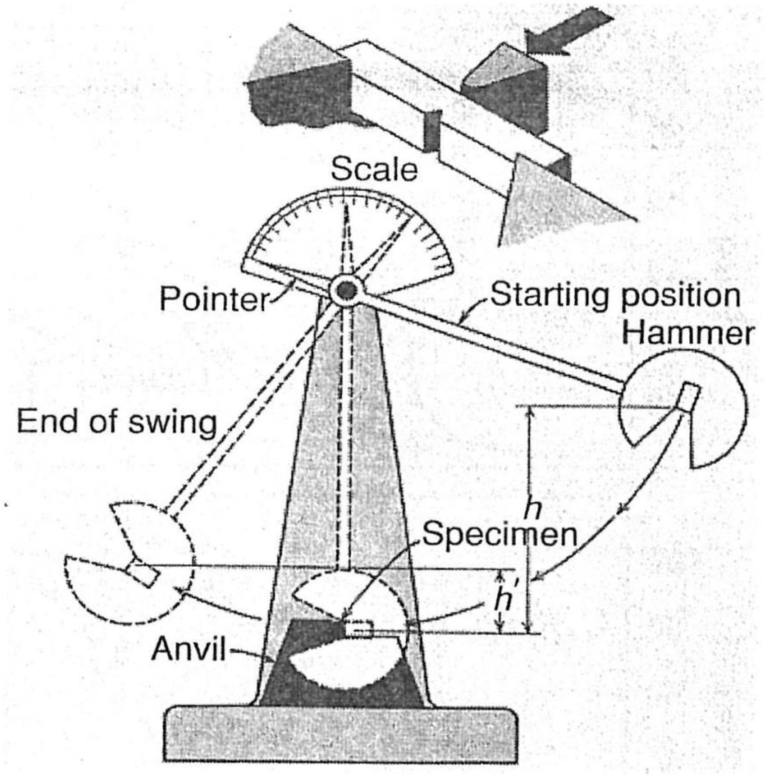
In a tension test, the energy per volume to cause failure is the area under the stress-strain curve and it is called toughness.

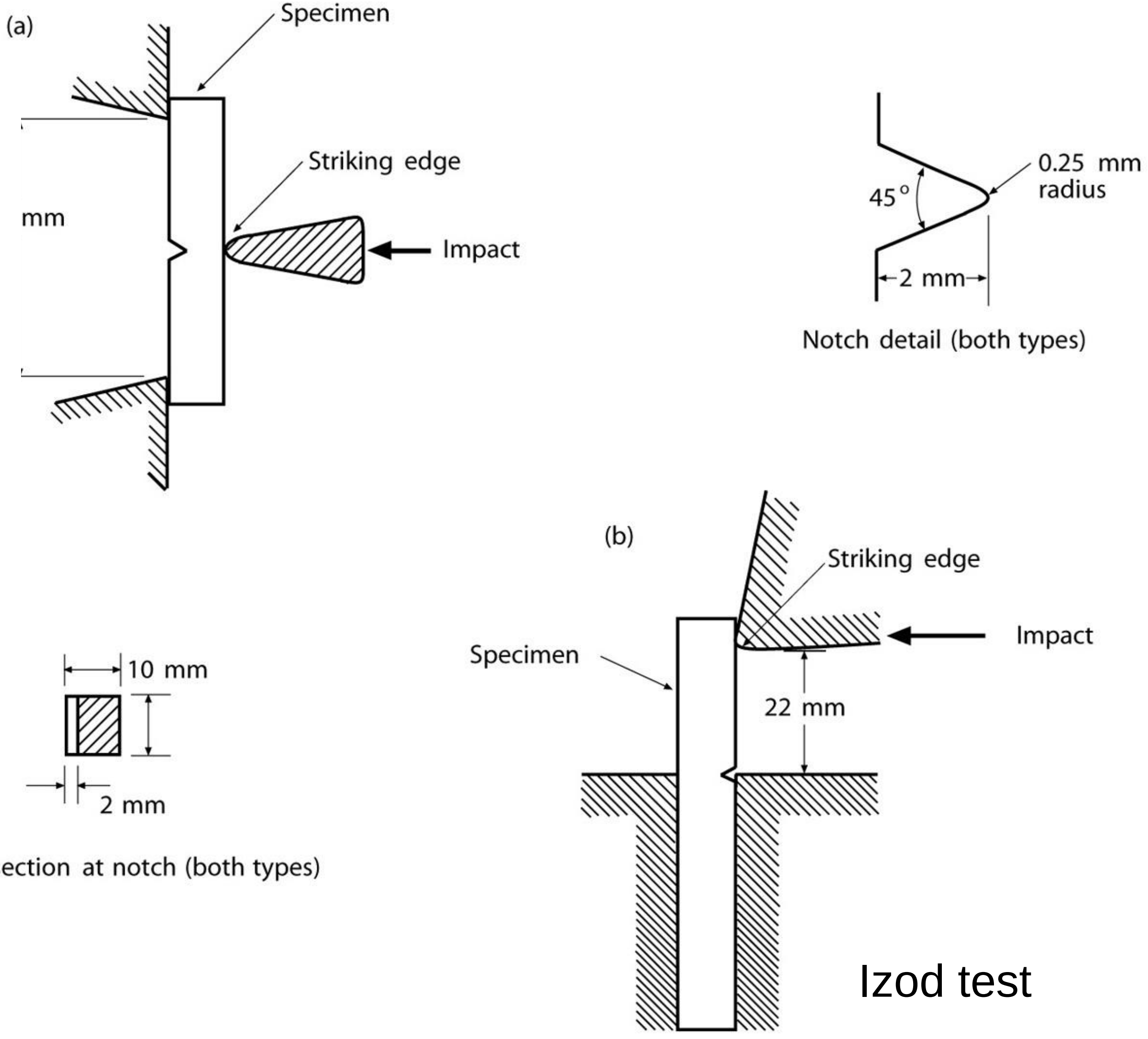
$$W = \frac{1}{2}\sigma_{ij}\varepsilon_{ij}$$



Impact test

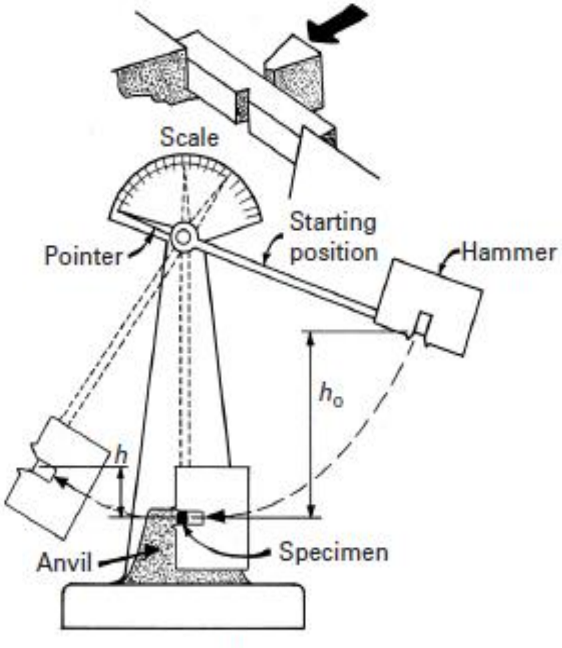
In Charpy test, the energy absorbed in the fracture is measured by recording how high the pendulum swings after the bar breaks.





Izod test

Measurement of impact energy



(a)

The sum of the energy of plastic deformation

$$E_f = mg(h_0 - h_1)$$

The Charpy energy

$$CV \approx mg(h_0 - h_1)$$

The strain rate in a Charpy test

$$v = \sqrt{2gh_0}$$

$$v = 4.5 m/s$$

$$\dot{\varepsilon} = \frac{v}{L} \approx 10^3 s^{-1}$$

For a difference in height of 1m and the average deformation length of 5mm

Fracture surface

4140 steel

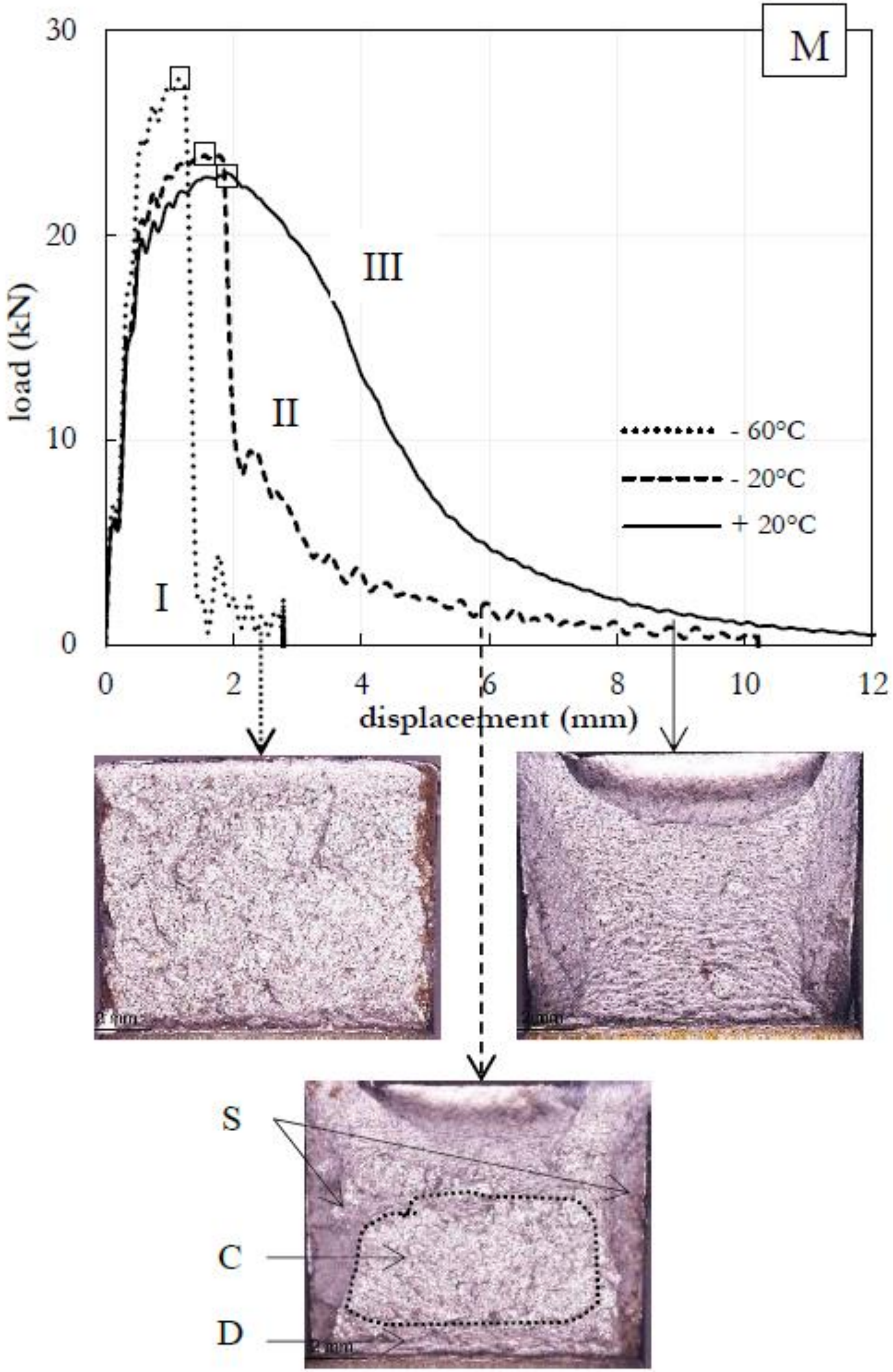
$\sigma_u = 1550 MPa$

Gray cast iron

4140 steel

$\sigma_u = 950 MPa$

Typical instrumented Charpy impact test (ICIT) curve

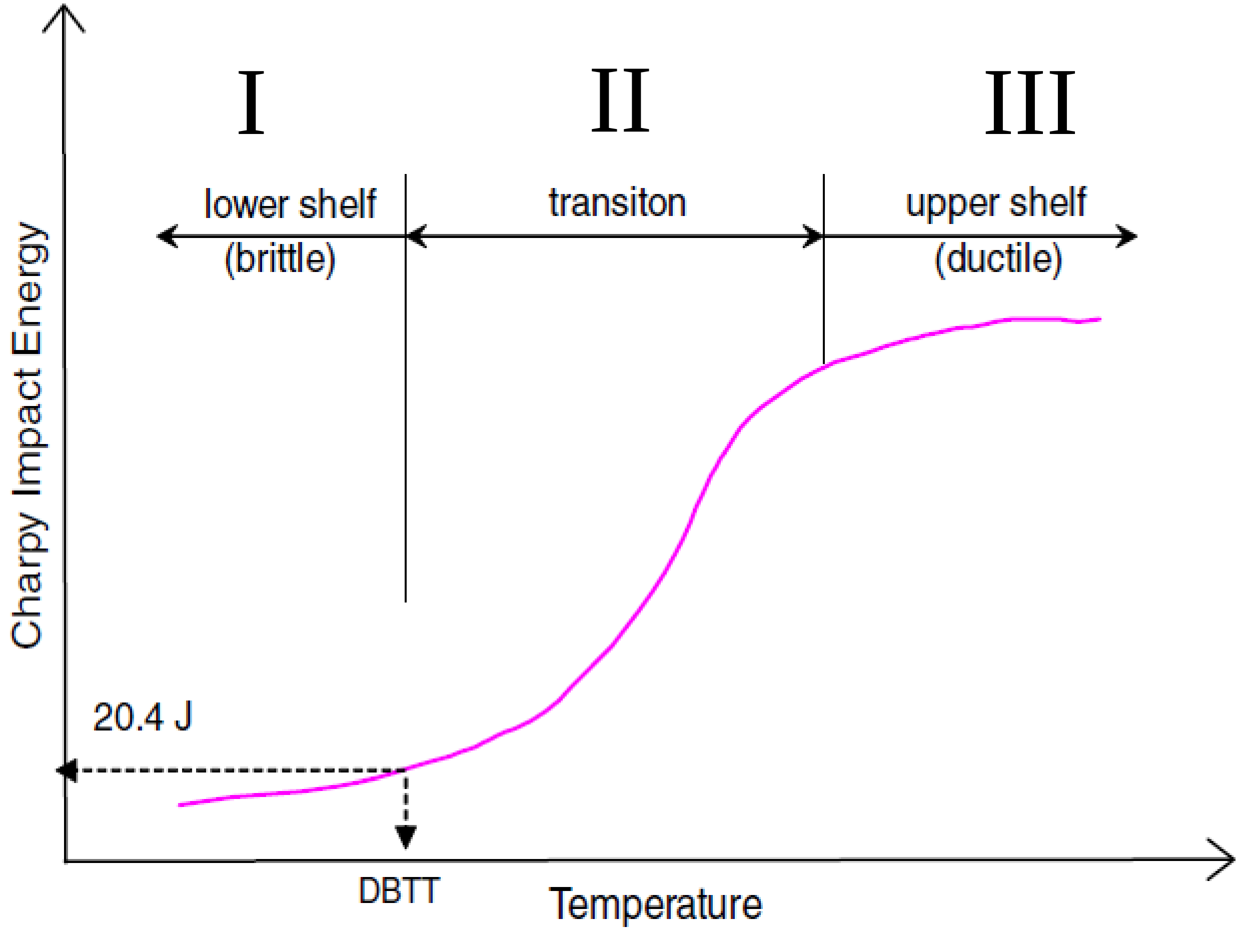


Type I: fully brittle fracture

Type II : mixed (brittle + ductile) fracture

Type III: fully ductile fracture

Charpy V-notch (CVN) impact energy vs. temperature



A ductile–brittle transition temperature (DBTT) is assigned to the curve at 20.4 J absorbed energy as a reference temperature defining the transition of fracture mode.

Effect of C content on impact energy

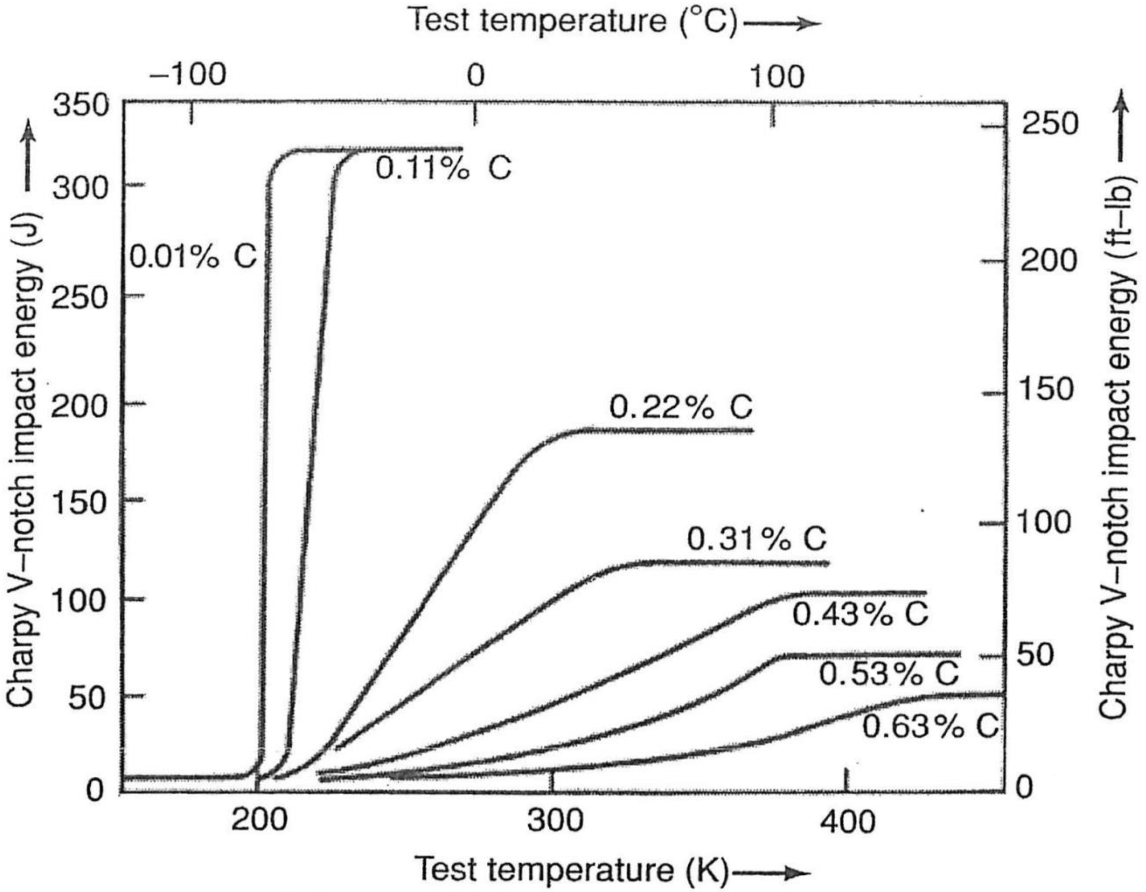
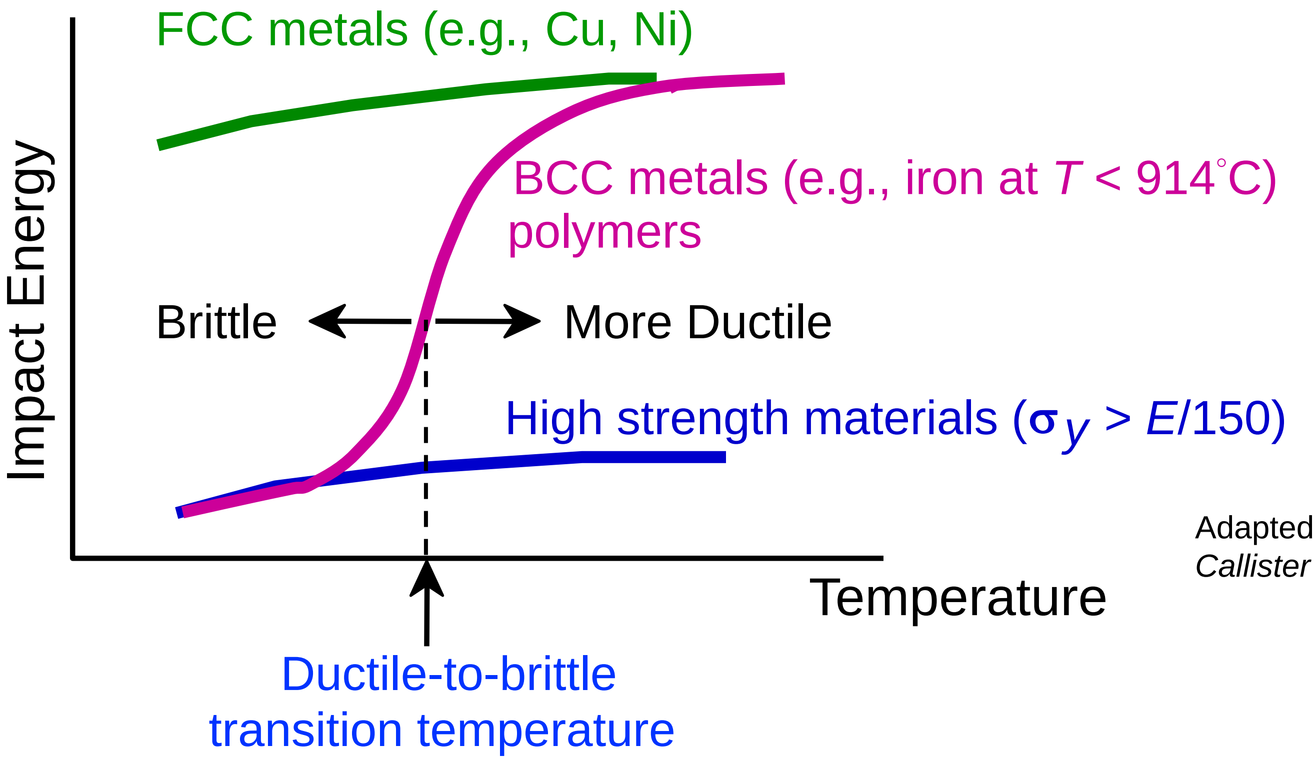


Figure 13.24. Effect of carbon content on Charpy V-notch impact energy. Decreasing carbon content lowers the ductile–brittle transition and raises the shelf energy. From J. A. Rinebilt and W. J. Harris, *Trans. ASM*, Vol. 43 (1951).

Ductile-brittle Transition temperature between fcc and bcc

- **Ductile-to-Brittle Transition Temperature (DBTT)...**



Adapted from Fig. 8.15, *Callister 7e.*

Ductile to Brittle transition occurs particularly in BCC metals only because in BCC metals have much larger P-N stress because of the less closed packed atoms . P-N stress is internal stress which may overcome by external shear stress in order to move the dislocations .

Impact Test (Charpy) Data for Some of the Alloys of Table 6.1

Alloy		Impact energy [J (ft·lb)]
1.	1040 carbon steel	180 (133)
2.	8630 low-alloy steel	55 (41)
3.	b. 410 stainless steel	34 (25)
4.	L2 tool steel	26 (19)
5.	Ferrous superalloy (410)	34 (25)
6.	a. Ductile iron, quench	9 (7)
7.	b. 2048, plate aluminum	10.3 (7.6)
8.	a. AZ31B magnesium	4.3 (3.2)
	b. AM100A casting magnesium	0.8 (0.6)
9.	a. Ti–5Al–2.5Sn	23 (17)
10.	Aluminum bronze, 9% (copper alloy)	48 (35)
11.	Monel 400 (nickel alloy)	298 (220)
13.	50:50 solder (lead alloy)	21.6 (15.9)
14.	Nb–1 Zr (refractory metal)	174 (128)

Impact Test (Izod) Data for Various Polymers

Polymer	Impact energy [J (ft·lb)]
General-use polymers	
Polyethylene	
High-density	1.4–16 (1–12)
Low-density	22 (16)
Polyvinylchloride	1.4 (1)
Polypropylene	1.4–15 (1–11)
Polystyrene	0.4 (0.3)
Polyesters	1.4 (1)
Acrylics (Lucite)	0.7 (0.5)
Polyamides (nylon 66)	1.4 (1)
Cellulosics	3–11 (2–8)
Engineering polymers	
ABS	1.4–14 (1–10)
Polycarbonates	19 (14)
Acetals	3 (2)
Polytetrafluoroethylene (Teflon)	5 (4)
Thermosets	
Phenolics (phenolformaldehyde)	0.4 (0.3)
Urea-melamine	0.4 (0.3)
Polyesters	0.5 (0.4)
Epoxies	1.1 (0.8)

Source: From data collections in R. A. Flinn and P. K. Trojan, *Engineering Materials and Their Applications*, 2nd ed., Houghton Mifflin Company, Boston, 1981; M. F. Ashby and D. R. H. Jones, *Engineering Materials*, Pergamon Press, Inc., Elmsford, NY, 1980; and *Design Handbook for Du Pont Engineering Plastics.*