Fracture

Subjects of interest

- Introduction/ objectives
- Types of fracture in metals
- Theoretical cohesive strength of metals
- The development in theories of brittle fracture
- Fractographic observation in brittle fracture
- Ductile fracture
- Ductile to brittle transition behaviour
- Intergranular fracture
- Factors affecting modes of fracture
- Concept of the fracture curve

Objectives

• This chapter provides the development in the theories of brittle fractures together with mechanisms of fracture that might occur in metallic materials.

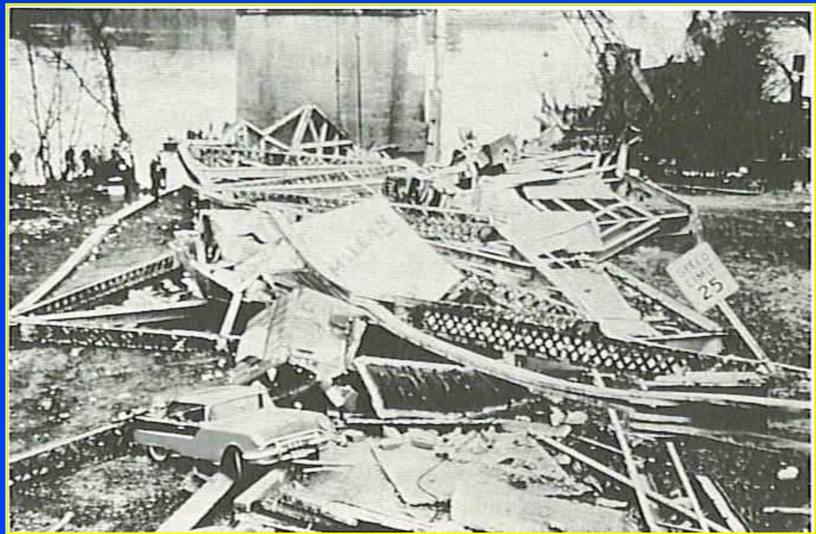
• Factors affecting different types of fracture processes such as brittle cleavage fracture, ductile failure or intergranular fracture will be discussed.

Introduction

Failure in structures leads to lost of properties and sometimes lost of human lives unfortunately.

Failed fuselage of the Aloha 737 aircraft in 1988.

Failure of Liberty Ships during services in World War II.



Collapse of Point Pleasant suspension bridge, West Virginia, 1967.

Types of fracture in metals

- *The concept of material strength and fractures has long been studied to overcome failures.*
- *The introduction of malleable irons during the revolution of material construction led to the perception of brittle and ductile fractures as well as fatigue failure in metals.*

Failure in metallic materials can be divided into two main categories;

Ductile failure

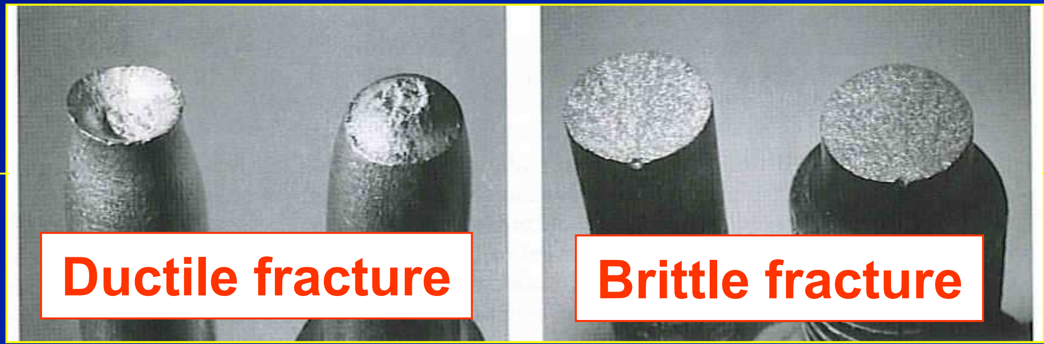
Ductile fracture involves a large amount of plastic deformation and can be detected beforehand.

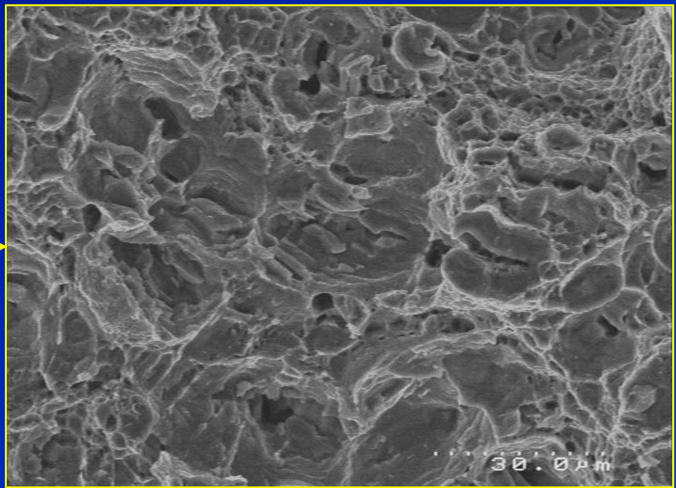
Brittle failure

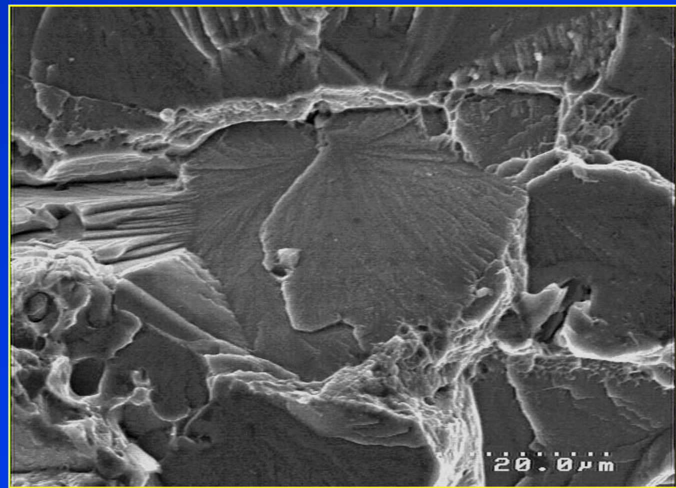
Brittle fracture is more catastrophic and has been intensively studied.

Theories of brittle fracture

Failure modes







- ***High energy** is absorbed by microvoid coalescence during ductile failure (high energy fracture mode)*

Less catastrophic

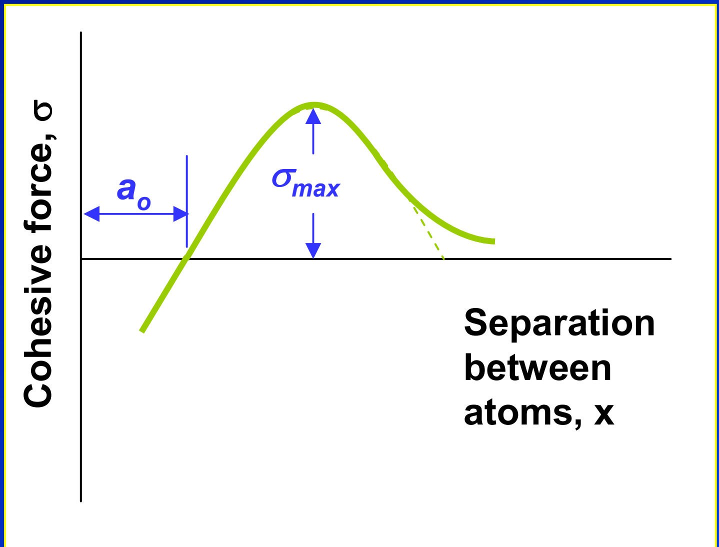
- ***Low energy** is absorbed during transgranular cleavage fracture (low energy fracture mode)*

More catastrophic

Theoretical cohesive strength of metal

• In the most basic term, strength is due to the ***cohesive forces between atoms***.

• The ***attractive*** and ***repulsive*** force acting on the two atoms lead to ***cohesive force*** between two atoms which varies in relation to the separation between these atoms, see *fig*.



Cohesive force as a function of the separation between atoms.

The ***theoretical cohesive strength*** σ_{max} can be obtained in relation to the sine curve and become.

$$\sigma_{max} = \left(\frac{E\gamma_s}{a_o} \right)^{1/2} \quad \text{...Eq. 1}$$

Where

γ_s is the surface energy

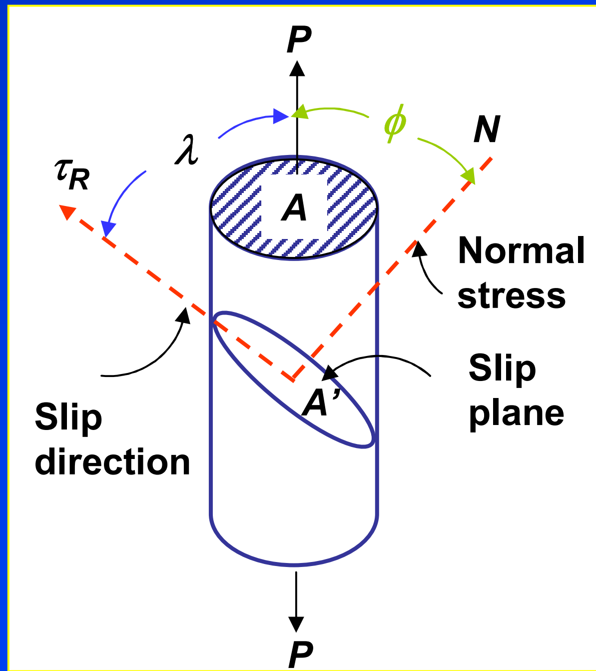
a_o is the unstrained interatomic spacing.

*Note: Convenient estimates of σ_{max} ~ **E/10**.*

Fracture in single crystals

The ***brittle fracture*** of single crystals is related to the resolved normal stress on the cleavage plane.

Sohncke's law *states that fracture occurs when the* ***resolved normal stress*** *reaches a critical value.*



From the critical resolved shear stress τ_R for slip

$$\tau_R = \frac{P\cos\lambda}{A/\cos\phi} = \frac{P}{A}\cos\phi\cos\lambda$$ *...Eq. 2*

The critical normal stress σ_c for brittle fracture

$$\sigma_c = \frac{P\cos\phi}{A/\cos\phi} = \frac{P}{A}\cos^2\phi$$ *...Eq. 3*

Note: shear stress → slip
tensile stress → crack propagation → fracture.

Example: ***Determine the cohesive strength of a silica fibre, if E = 95 GPa, γ_s = 1 J.m^{-2}, and a_o = 0.16 nm.***

$$\sigma_{\max} = \left(\frac{E\gamma_s}{a_o}\right)^{1/2} = \left(\frac{95\times10^{9}\times1}{0.16\times10^{-9}}\right)^{1/2} = 24.4 \ \ GPa$$

- This ***theoretical cohesive strength*** is exceptionally higher than the fracture strength of engineering materials.
- This difference between cohesive and fracture strength is due to ***inherent flaws or defects*** in the materials which lower the fracture strength in engineering materials.
- ***Griffith*** explained the discrepancy between the ***fracture strength*** and theoretical cohesive strength using the ***concept of energy balance***.

Theories of brittle fracture

Griffith theory of brittle fracture

The first analysis on cleavage fracture was initiated by ***Griffith*** using ***the concept of energy balance*** in order to explain discrepancy between the theoretical cohesive strength and observed fracture strength of ideally brittle material.

The development in cleavage fracture models

- ***Modified Griffith theory*** *by Irwin and Orowan.*
- ***Zener's model*** *of microcrack formation at a pile-up of edge dislocations.*
- ***Stroh's model*** *of cleavage crack formation by dislocation pile-up.*
- ***Cottrell's model*** *of cleavage crack initiation in BCC metals*
- ***Smith's model*** *of microcrack formation in grain boundary carbide film.*

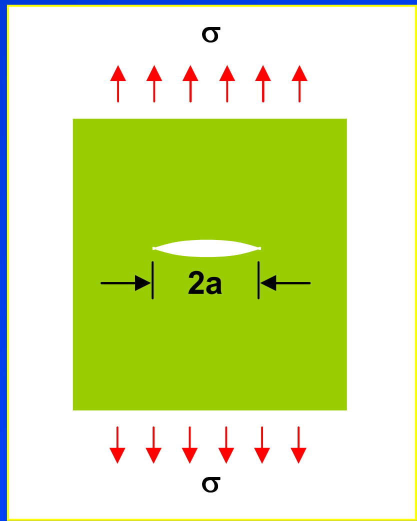
Griffith theory of brittle fracture

Observed fracture strength is always lower than theoretical cohesive strength

Griffith explained that the discrepancy is due to the ***inherent defects*** in brittle materials leading to stress concentration. → lower the fracture strength of the materials

Crack propagation criterion:

Consider a through thickness crack of length ***2a,*** subjected to a uniform tensile stress σ, at infinity.



Griffith crack model

Crack propagation occurs when the released elastic strain energy is at least equal to the energy required to generate new crack surface.

- The stress required to create the new crack surface is given as follows;

$$\sigma = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2} \quad \text{...Eq. 4}$$

- In plane strain condition, *Eq.4* becomes

$$\sigma = \left(\frac{2E\gamma_s}{(1-\upsilon^2)\pi a} \right)^{1/2} \quad \text{...Eq. 5}$$

The Griffith's equation

Modified Griffith equation

- The ***Griffith equation*** is strongly dependent on the crack size ***a***, and satisfies only ***ideally brittle materials*** like glass.

- However, ***metals*** are not ideally brittle and normally fail with certain amounts of plastic deformation, the fracture stress is increased due to ***blunting of the crack tip***.

- ***Irwin*** and ***Orowan*** suggested ***Griffith's equation*** can be applied to ***brittle materials*** undergone plastic deformation before fracture by including the plastic work, γ_p, into the total elastic surface energy required to extend the crack wall, giving the ***modified Griffith's equation*** as follows

$$\boxed{\sigma_f = \left[\frac{2E(\gamma_s + \gamma_p)}{\pi(1-\upsilon^2)a}\right]^{1/2} \approx \left(\frac{E\gamma_p}{(1-\upsilon^2)a}\right)^{1/2} \quad , when \;\; \gamma_p >> \gamma_2} \qquad \text{...Eq. 6}$$

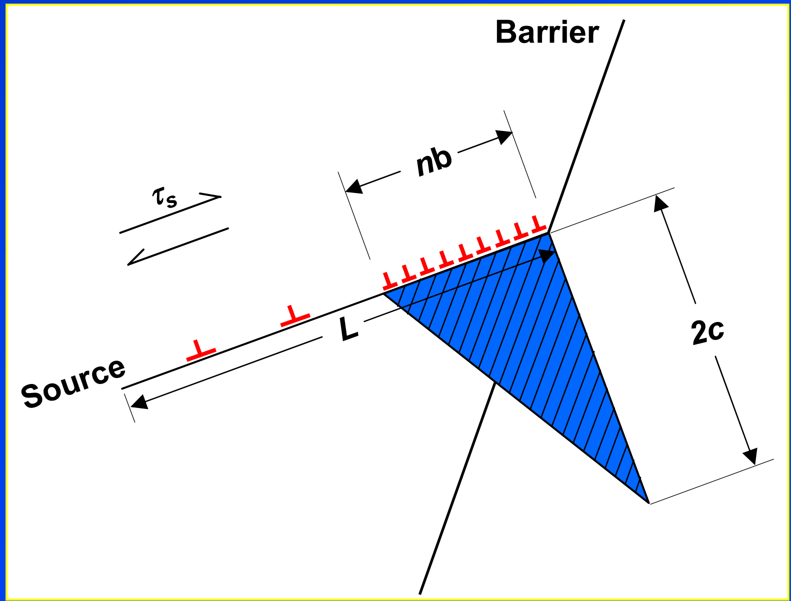
Zener's model of microcrack formation at a pile-up of edge dislocations

The ***Griffith theory*** only indicated the stress required for crack propagation of an existing crack of length ***2a*** but did not explain the ***nucleation of the crack***.

Zener and ***Stroh*** showed that the crack nucleation of length ***2c*** occurs when the shear stress τ_s created by ***pile-up*** of ***n*** dislocations of ***Burgers vector*** **b** at a grain boundary reaches the value of

$$\tau_s \approx \tau_i + \left(\frac{2\gamma_s}{nb}\right) \qquad \text{...Eq. 7}$$

Where τ_i is the lattice friction stress in the slip plane.



Dislocation pile-ups at barrier.

Stroh's model of cleavage crack formation by dislocation pile-up

Stroh included the effect of the grain size ***d*** in a model, suggesting the condition of the shear stress created by ***dislocation pile-up*** of the length ***d/2*** to nucleate a ***microcrack*** as follows

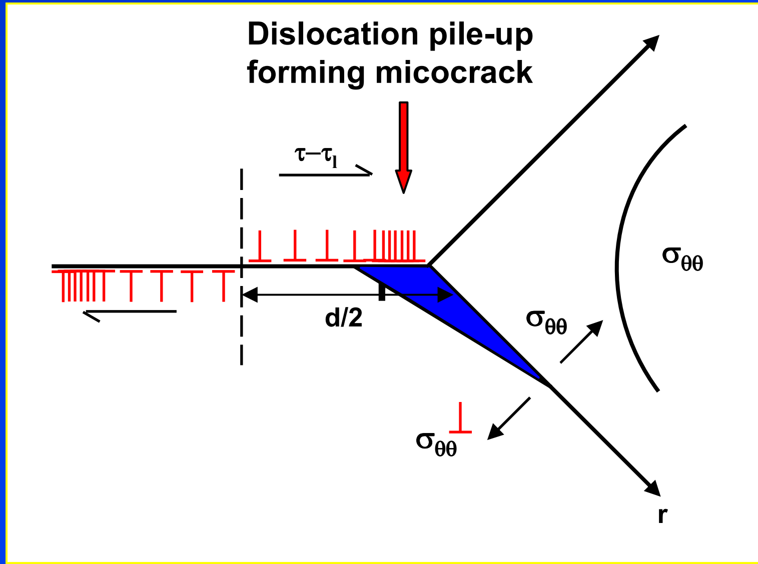
$$\tau_{eff} = \tau_y - \tau_i \sqrt{\frac{E\pi\gamma}{4(1-\upsilon^2)d}} \qquad \text{...Eq. 8}$$

where

τ_{eff} is the effective shear stress

τ_y is the yield stress

<u>Note:</u> This model indicates that the fracture of the material should depend only on the ***<u>shear stress</u>*** acting on the slip band.



Stroh's model of cleavage crack formation by dislocation pile-up.

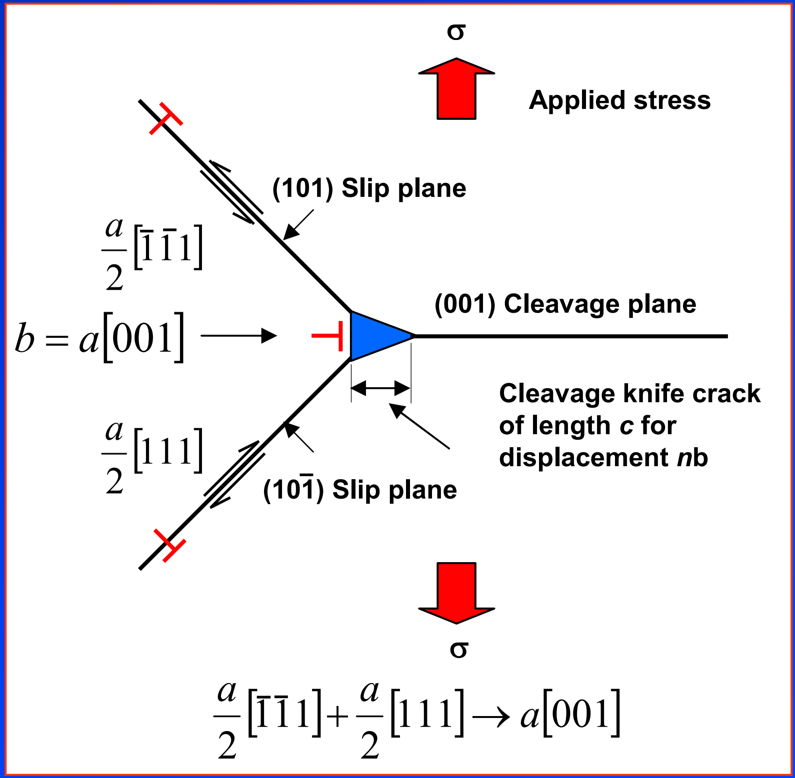
Cottrell's model of cleavage crack initiation in BCC metals

Cottrell later suggested that the fracture process should be controlled by ***the critical crack growth stage*** under the applied tensile stress, which required higher stress than the ***crack nucleation*** itself as suggested by ***Stroh***.

Cottrell also showed that the ***crack nucleation stress*** can be small if the microcrack is initiated by ***intersecting of two low energy slip planes*** to provide a preferable cleavage plane.

$$\frac{a}{2}[\bar{1}\bar{1}1]+\frac{a}{2}[111]\rightarrow a[001] \qquad \text{...Eq. 9}$$

This results in a wedge cleavage crack on the (001) plane. Further propagation of this crack is then controlled by the applied tensile stress.



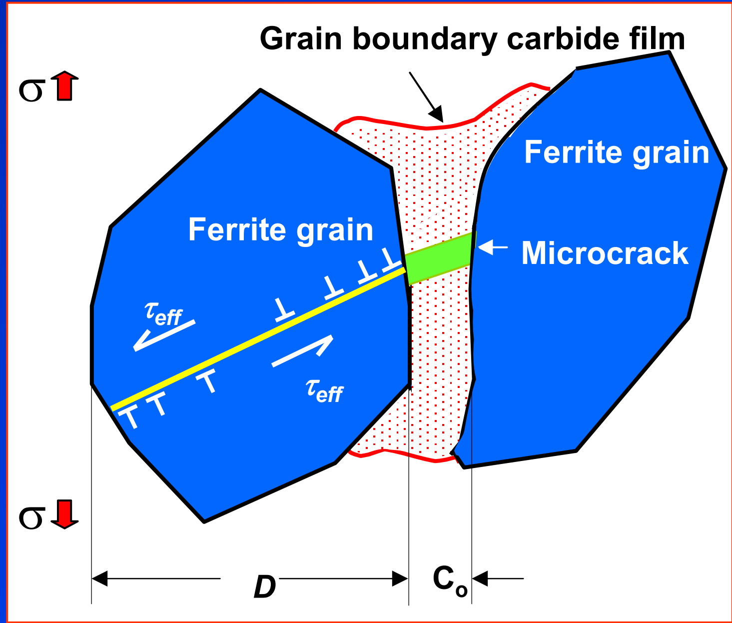
Cottrell's model of cleavage crack initiation in BCC metals

Smith's model of microcrack formation in grain boundary carbide film

Models proposed by ***Stroh*** and ***Cottrell*** involve ***crack initiation by dislocation pile-up*** of length ***D/2,*** but exclude the effect of ***second phase particles***.

Smith then proposed ***a model for cleavage fracture in mild steel*** concerning microcracking of grain boundary carbide by dislocation pile-up of length equal to half of the grain diameter ***D/2***.

Microcrack is initiated when sufficiently high applied stress causes local plastic strain within the ***ferrite grains*** to nucleate microcrack in brittle grain boundary carbide of thickness C_o.



Smith's model of microcrack formation in grain boundary carbide film

$$\sigma_f^2\left(\frac{c_o}{d}\right)+\tau_{eff}^2\left\{1+\frac{4}{\pi}\left(\frac{C_o}{d}\right)^{1/2}\frac{\tau_i}{\tau_{eff}}\right\}^2 \geq \frac{4E\gamma_p}{(1-\upsilon^2)\pi d} \qquad \text{...Eq. 10}$$

*Note: Further propagation of the GB carbide crack follows the **Griffith theory**.*

Fractographic observation in brittle fracture

The process of cleavage fracture consists of three steps:

1) Plastic deformation to produce dislocation pile-ups.

2) Crack initiation.

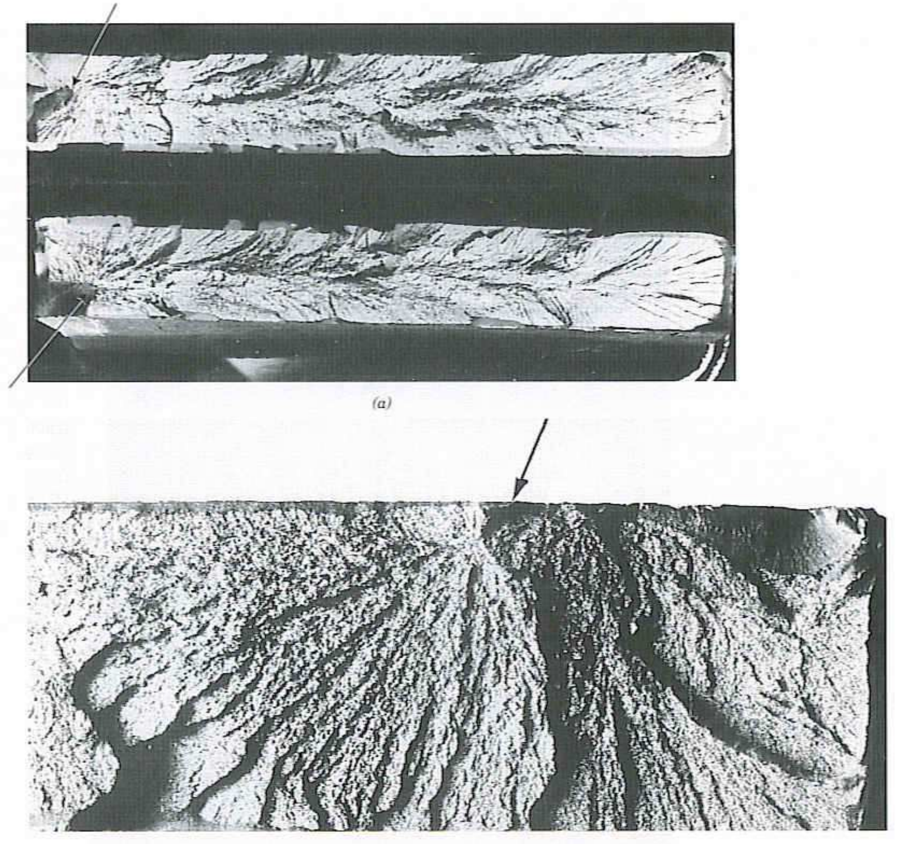
3) Crack propagation to failure.

Distinct characteristics of brittle fracture surfaces:

1) The absence of gross plastic deformation.

2) Grainy or Faceted texture.

3) River marking or stress lines.



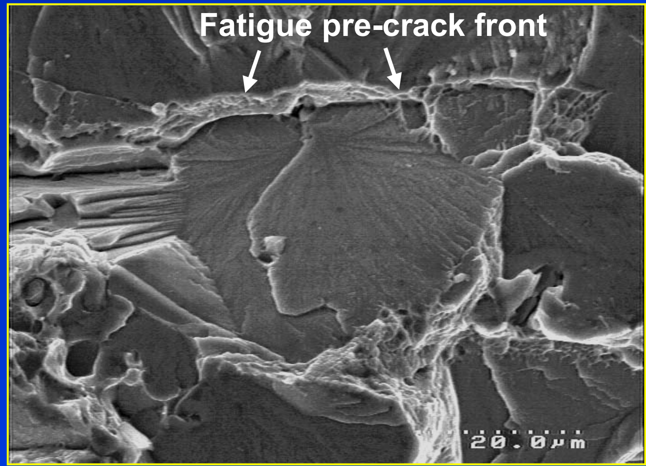
(a)

(b)

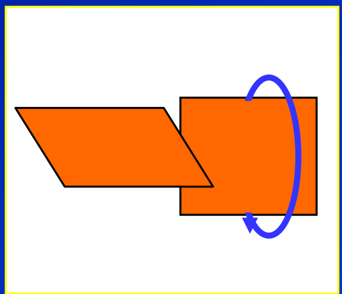
Brittle fracture indicating the origin of the crack and crack propagation path

Brittle fracture surface

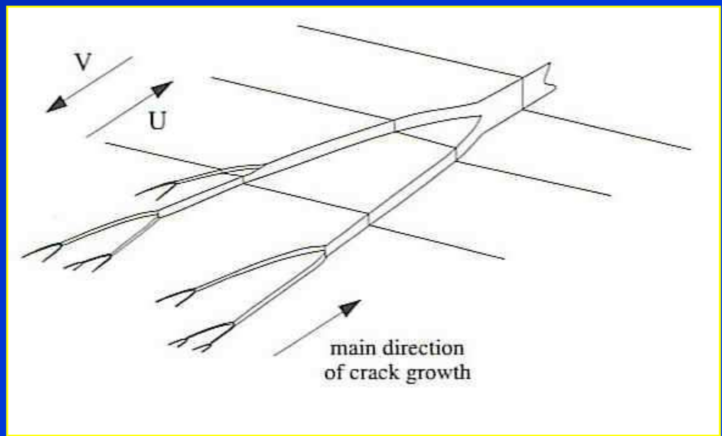
- ***Cleavage fracture surface*** is characterised by flat facets (with its size normally similar to the grain size).
- ***River lines*** or the ***stress lines*** are steps between cleavage on parallel planes and always converge in the direction of local crack propagation.



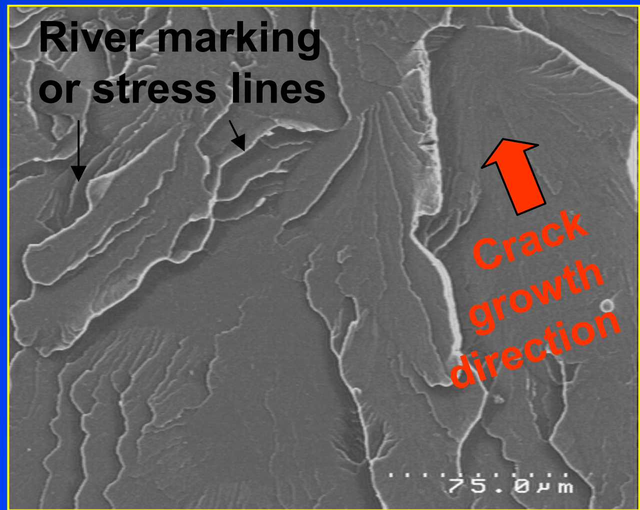
Cleavage facet



Twist boundary



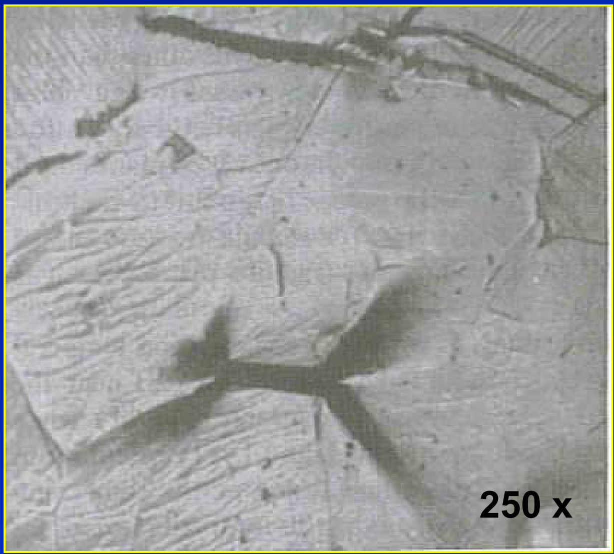
Schematic of river-line pattern.



Brittle cleavage facet

Initiation of microcracks from deformation and twins

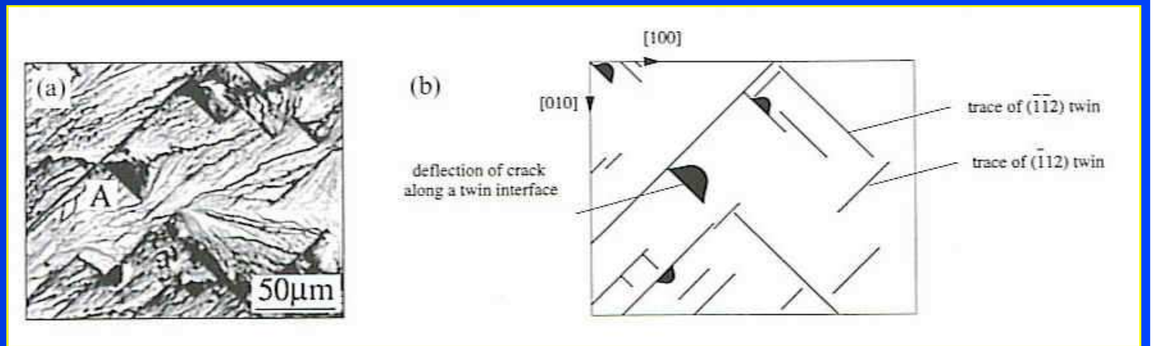
• ***Microcracks*** can be produced by the deformation process, see *fig*.



Microcracks produced in iron by tensile deformation at 133 K.

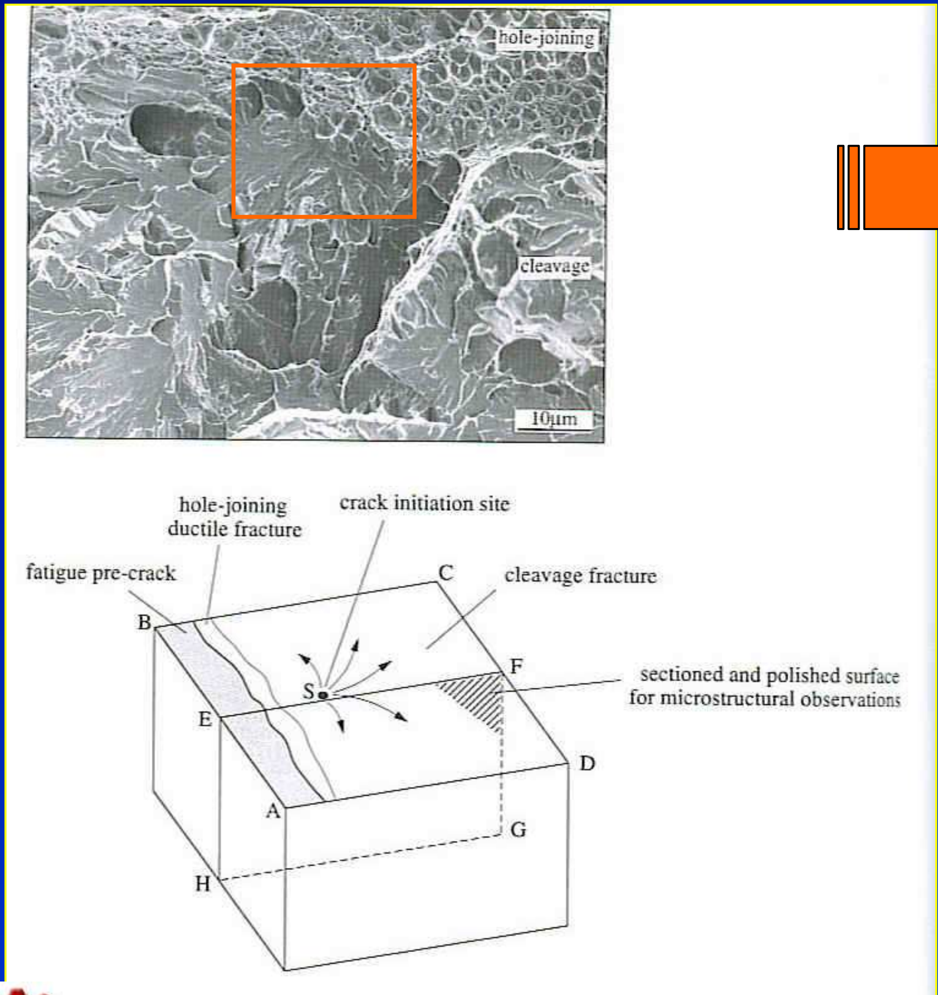
• ***Microcracks*** can also be initiated at ***mechanical twins***, especially in large grained bcc metals at low temperature.

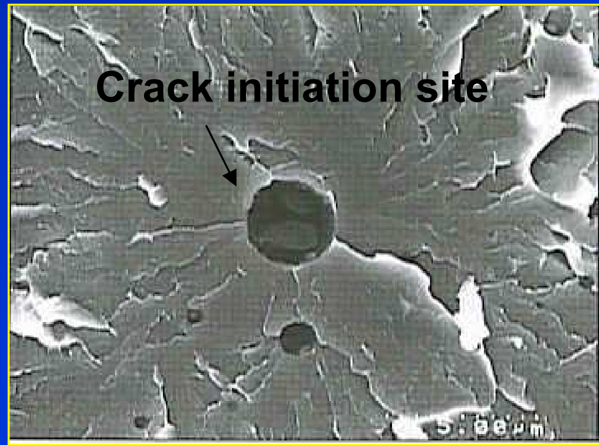
• Crack initiation sites are due to the intersections of twins with other twins or intersection of twins with grain boundaries.



Cleavage along twin-matrix interfaces.

Crack initiation from particles in cleavage fracture

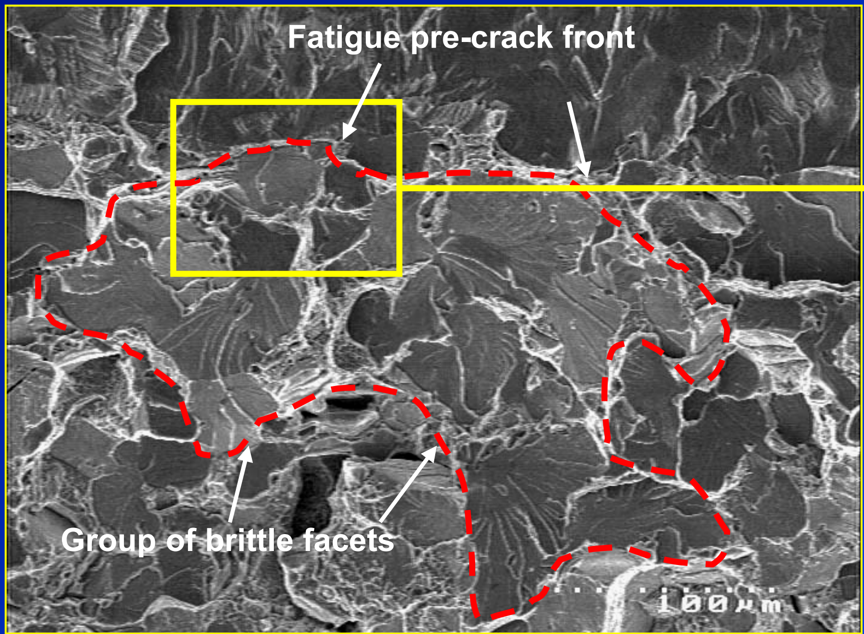


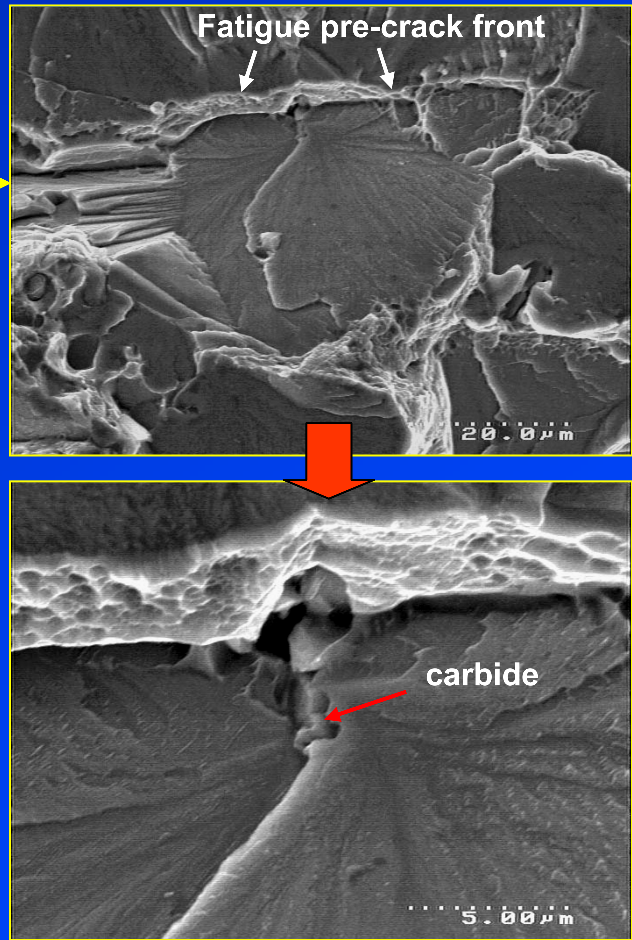


- Inclusions, porosity, second-phase particles or precipitates are preferential sites (***stress raiser***) for cleavage initiation.
- Fracture occurs along the ***crystallographic planes***.
- The direction of the river pattern represents the ***direction of the crack propagation***.

Example: ***Crack initiation from carbide particles observed in β-Ti alloy.***

Titanium carbides act as ***stress raiser*** which are preferential site for transgranular cleavage fracture.

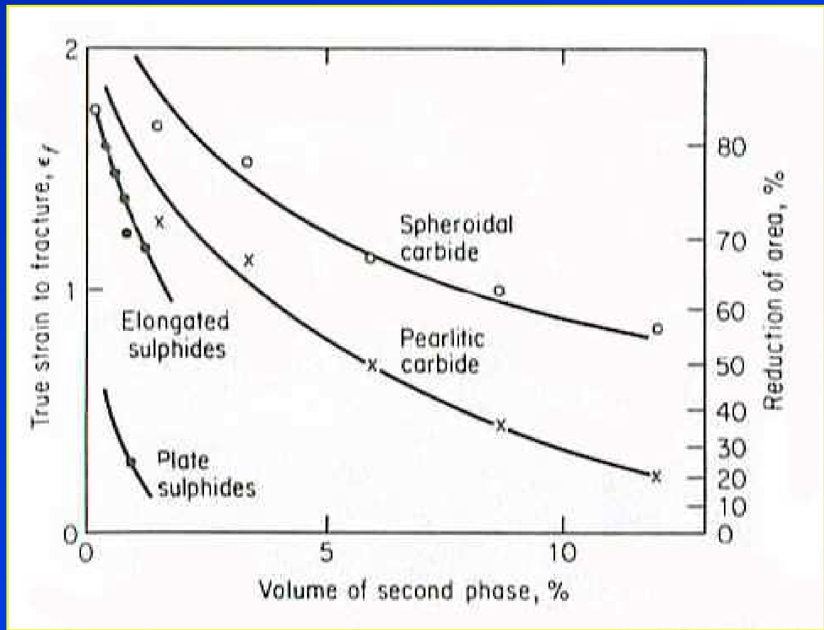




High local tensile stresses raised by dislocation pile-ups ahead of the carbide cause micro-cracking of carbide, which further propagate to cause global failure.

Effects of second phase particles on tensile ductility

• Second-phase particles which are ***readily cut by dislocation*** produce ***planar slips***, producing large dislocation pile-ups which are susceptible for brittle fracture.

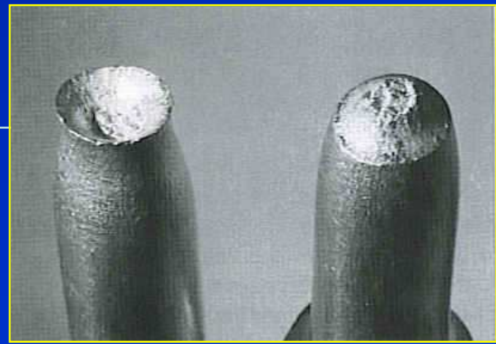


• Second-phase particles which are ***impenetrable by dislocations***, greatly ***reduce the slip distance*** → the number of dislocations is sustained → reduce the pile-up.

• Small spherical particles ***(r<1 μm)*** are more resistant to cracking.

• A soft ductile phase can also impart ductility to a brittle matrix.

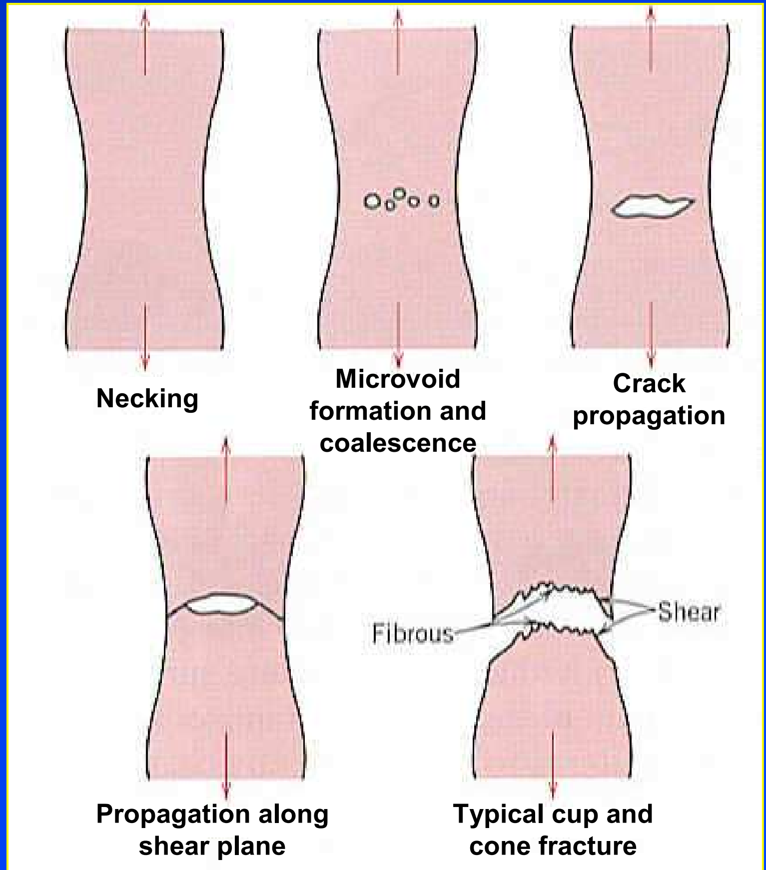
Ductile fracture



*Ductile fracture is a much less serious problem in engineering materials since failure can be detected beforehand due to observable **plastic deformation** prior to failure.*

• Under uniaxial tensile force, after necking, ***microvoids*** form and coalesce to form crack, which then propagate in the direction normal to the tensile axis.

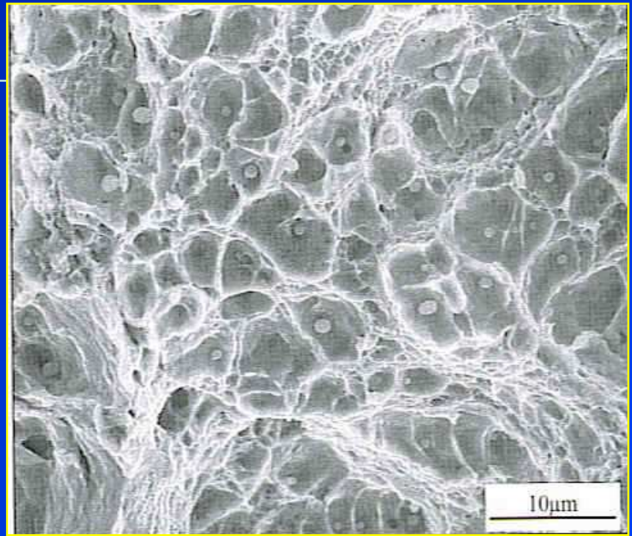
• The crack then rapidly propagate through the periphery along the shear plane at 45^o, leaving the ***cub and cone fracture***.



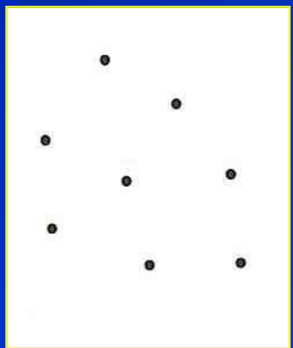
Stages in cup and cone fracture

Microvoid formation, growth and coalescence

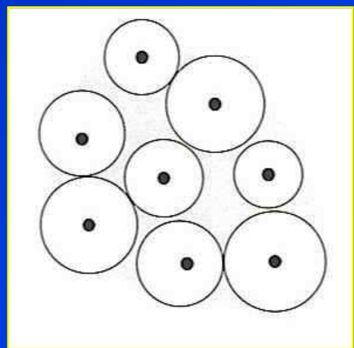
- ***Microoids*** are easily formed at inclusions, intermetallic or second-phase particles and grain boundaries.
- ***Growth*** and ***coalescence*** of microvoids progress as the local applied load increases.



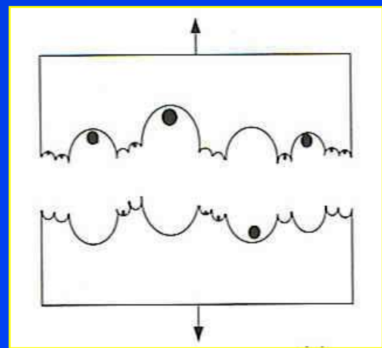
Ductile dimples centred on spherical particles



a) Random planar array of particles acting as void initiators.



b) Growth of voids to join each other as the applied stress increases.

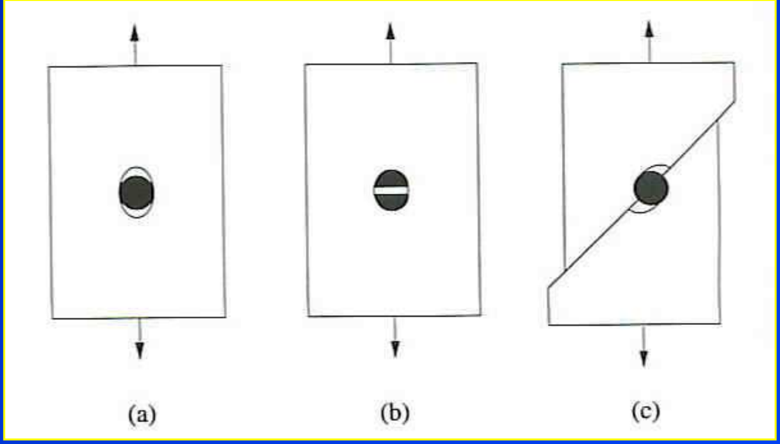


c) Linkage or coalescence of these voids to form free fracture surface.

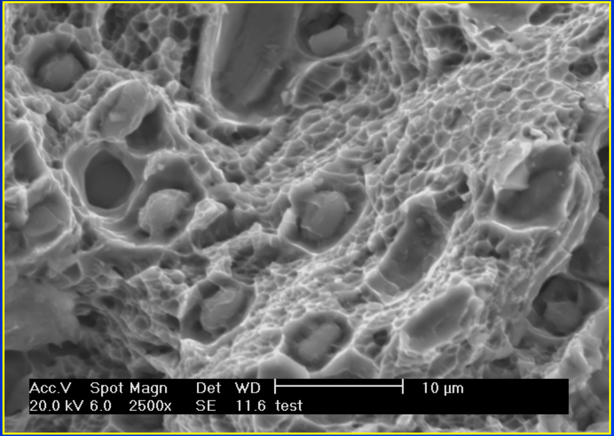
Formation of microvoids from second phase particles

Microvoids are formed by

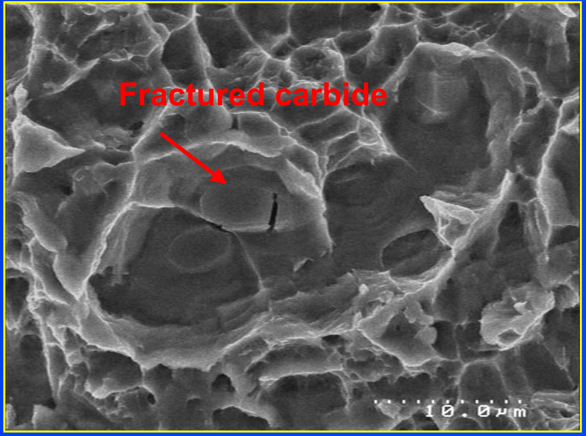
1) Decohesion at particle-matrix interface.
2) Fracture of brittle particle
3) Decohesion of an interface associated with shear deformation or grain boundary sliding.



Mechanisms of microvoid formation



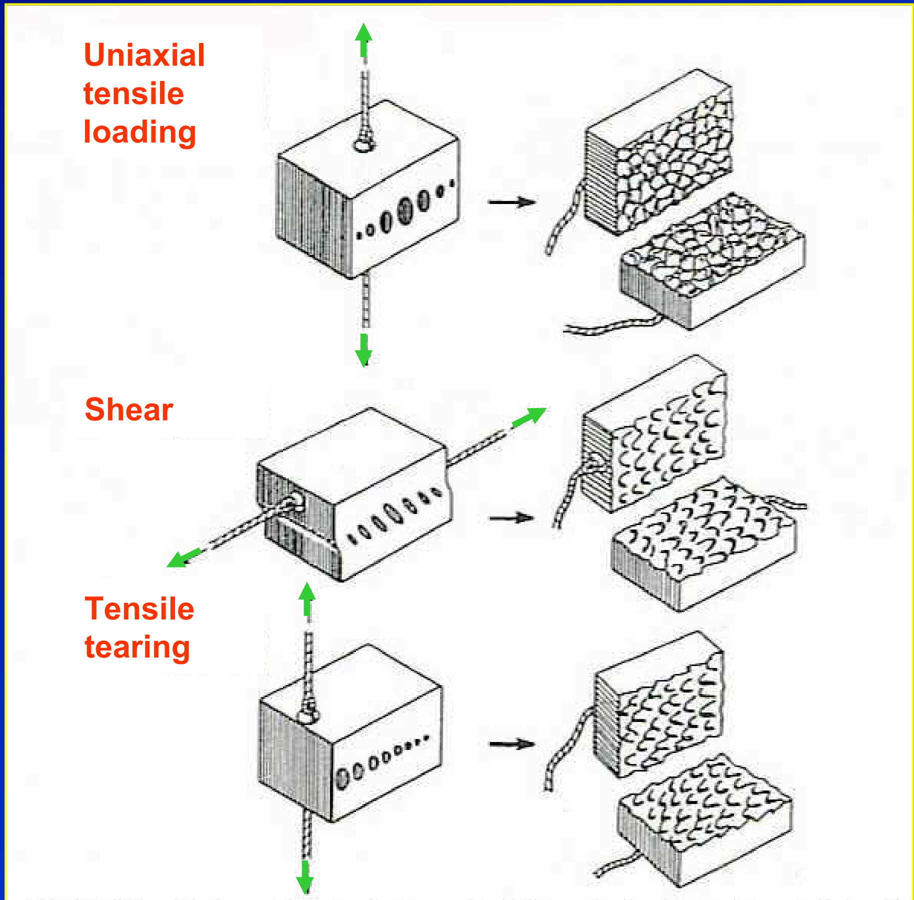
Decohesion of carbide particles from Ti matrix.



Fractured carbides aiding microvoid formation.

Microvoid shape

Microvoid shape is strongly influenced by the type of loading.



Uniaxial tensile loading
→ Equiaxed dimples.

Shear loading
→ Elongated and parabolic dimples pointing in the opposite directions on matching fracture surfaces.

Tensile tearing
→ Elongated dimples pointing in the same direction on matching fracture surface.

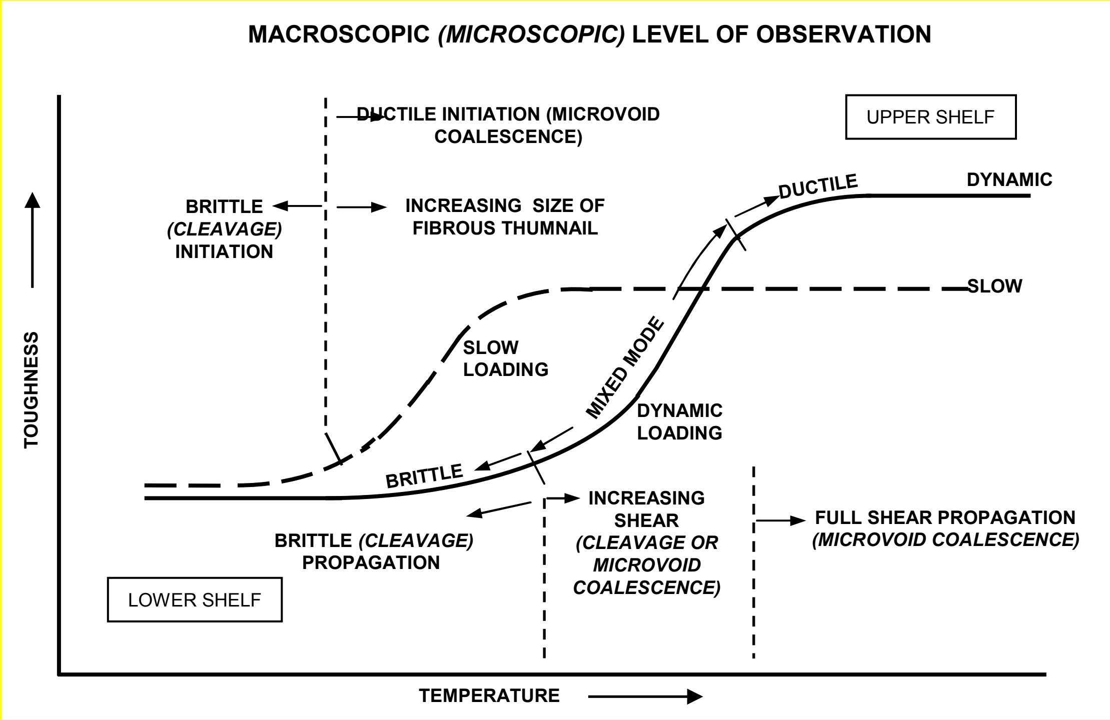
Formation of microvoids or dimples owing to uniaxial tensile loading, shear and tensile tearing

Ductile to brittle transition behaviour

BCC structure metals *experience* ***ductile-to-brittle transition behaviour*** *when subjected to decreasing temperature, resulting from a strong yield stress dependent on temperature.*

- ***BCC*** metals possess ***limited slip systems*** available at low temperature, ***minimising the plastic deformation*** during the fracture process.

- ***Increasing temperature*** allows more slip systems to operate, yielding ***general plastic deformation*** to occur prior to failure.



Low temperature → **Brittle cleavage fracture**

High temperature → **Ductile fracture**

Theory of the ductile to brittle transition

The *criterion* for a material to change its fracture behaviour from ***ductile to brittle mode*** is when the ***yield stress*** at the observed temperature is larger than the ***stress necessary for the growth of the microcrack*** indicated in the ***Griffith theory***.

Cottrell studied the role of parameters, which influence the ***ductile-to-brittle transition*** as follows;

...Eq. 11

$$\left(\tau_i D^{1/2} + k'\right)k' = G\gamma_s \beta$$

The criterion for ductile to brittle transition is when the term on the left hand side is greater than the right hand side.

where

τ_i is the lattice resistance to dislocation movement

k' is a parameter related to the release of dislocation into a pile-up

D is the grain diameter (associated with slip length).

G is the shear modulus

β is a constant depending on the stress system.

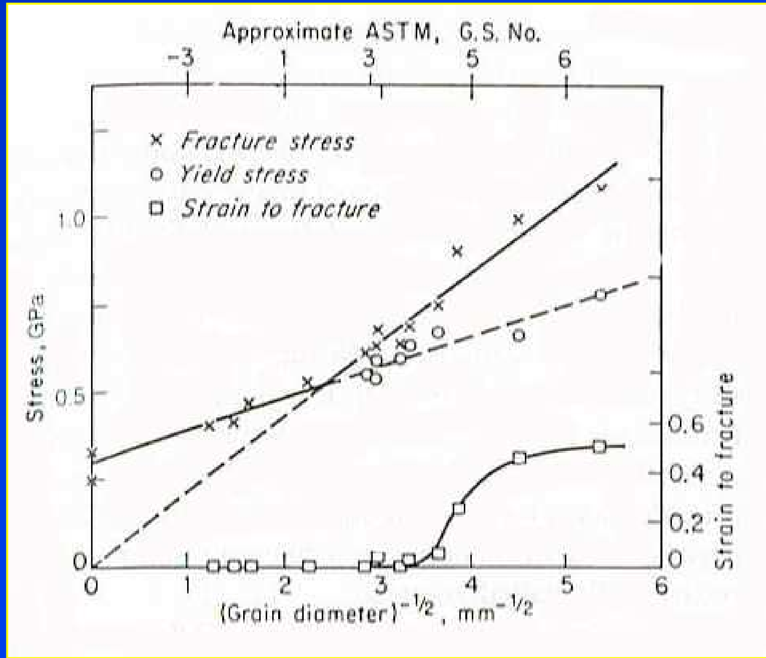
Factors affecting ductile to brittle transition

*From equation, materials having high lattice resistance τ_i ,grain size **D** and **k'** has a high tendency to become brittle with decreasing temperature.*

$$\left(\tau_i D^{1/2} + k'\right)k' = G\gamma_s\beta$$

- The τ_i in **BCC** material is strongly dependent on temperature.
- Materials with high ***k'*** i.e., ***Fe*** and ***Mo*** are more susceptible for brittle fracture.
- Smaller grain sized metals can withstand brittle behaviour better.

Note: Alloy chemistry and microstructure also affect the ductile to brittle transition behaviour.



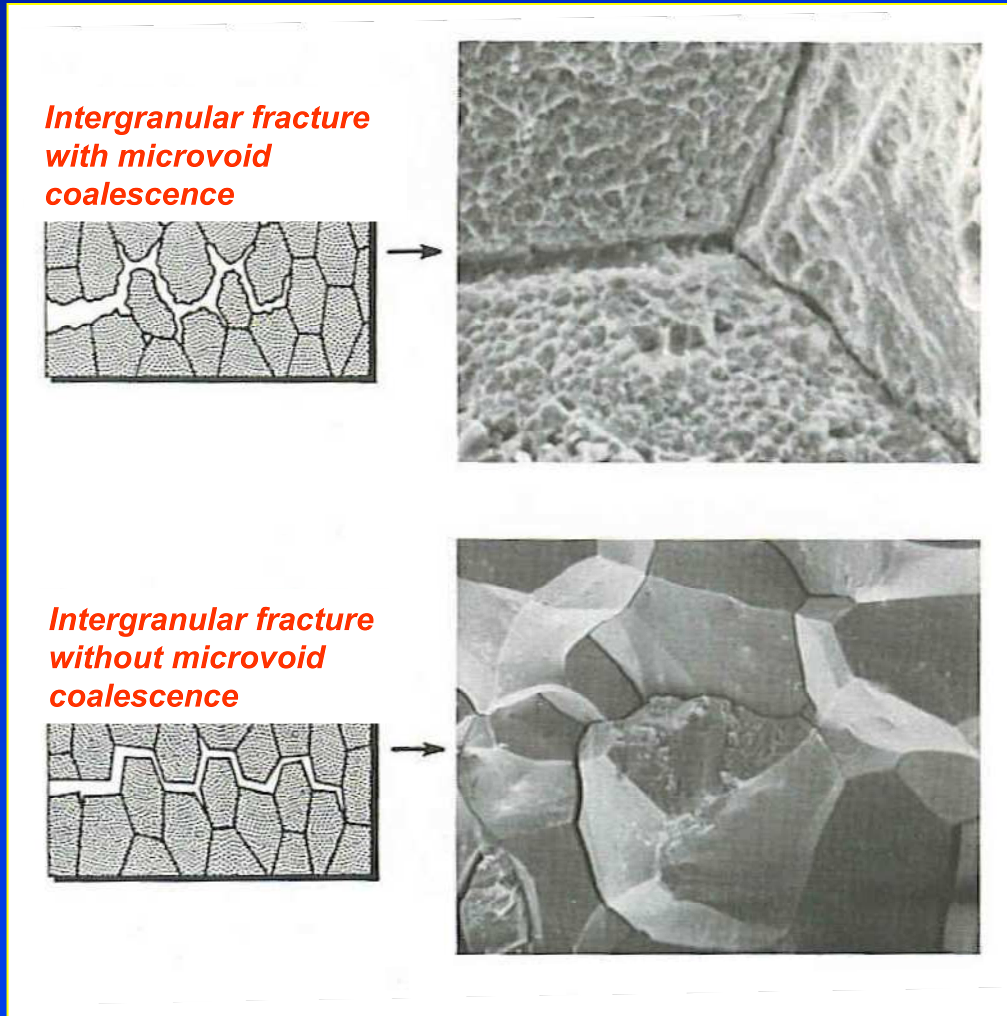
Effect of grain size on the yield and fracture stresses for a low-carbon steel tested in tension at -196°C.

In mild steel Ni lowers DBTT
C, P, N, S, Mo raise DBTT

Intergranular fracture

• ***Intergranular failure*** is a moderate to low energy brittle fracture mode resulting from ***grain boundary separation*** or segregation of embrittling particles or precipitates.

• ***Embrittling grain boundary particles*** are weakly bonded with the matrix, → high free energy and unstable, which leads to ***preferential crack propagation path***.



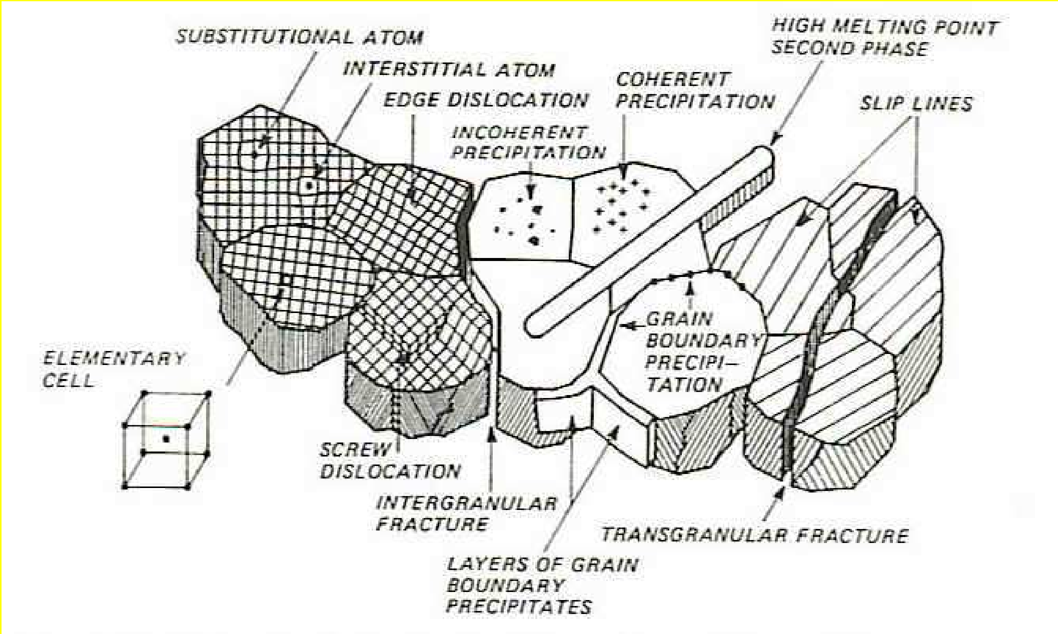
Intergranular fracture with and without microvoid coalescence.

Factors affecting modes of fracture

	Brittle fracture	Ductile fracture
Metallurgical aspect	Large grained materials with GB particles.	Fine grained material without GB particles.
Temperature	Low temperature	High temperature
State of stresses (notch effect)	Triaxial state of stresses (notch effect)	Absence of the notch
Strain rate	High strain rate	Low strain rate
Loading condition		Hydrostatic pressure (suppress crack initiation)

Metallurgical aspect of fracture

- Microstructure in metallic materials are highly complex.
- Various microstructural features affect how the materials fracture.



Microstructural features in metallic materials

There are microstructural features that can play a role in determining the fracture path, the most important are;

Second phase

Particles and precipitates

Grain size

Fibering and texturing

- ***High strength materials*** usually possess several microstructural features in order to optimise mechanical properties by ***influencing deformation behaviour / fracture paths***.

State of stresses (notch effect)

The difference in the state of stresses in the presence of a sharp crack or notch affects fracture in materials.

A notch or a sharp crack increases the ***tendency for brittle fracture*** in four important ways;

1) **Producing high local stresses**
2) **Introducing a triaxial state of stresses**
3) **Producing high local strain hardening and cracking**
4) **Producing a local magnification to the strain rate.**

*Note: the notch also raises the **plastic-constraint factor q,** which does not exceed the value of 2.75*

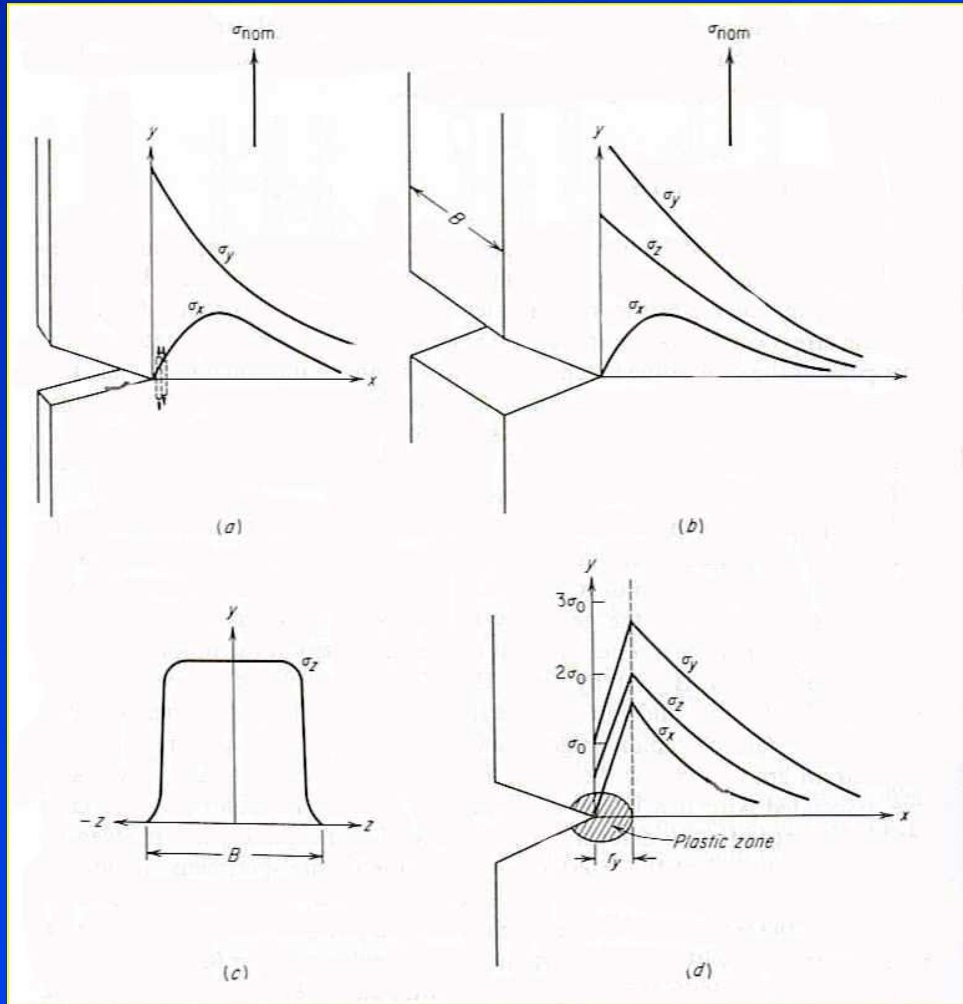
notch effect

The presence of the notch alters stress distribution

- In a thin plate, stress in the *z* (thickness) direction is absence, the specimen is not constrained.

- In thicker plate, σ_y (in the tensile direction) is constrained due to the reaction of σ_z and σ_x, leading to triaxial state of stresses.

- ***Triaxial stresses*** limit plastic deformation ahead of the crack tip → raising the general yield → material prone to brittle fracture



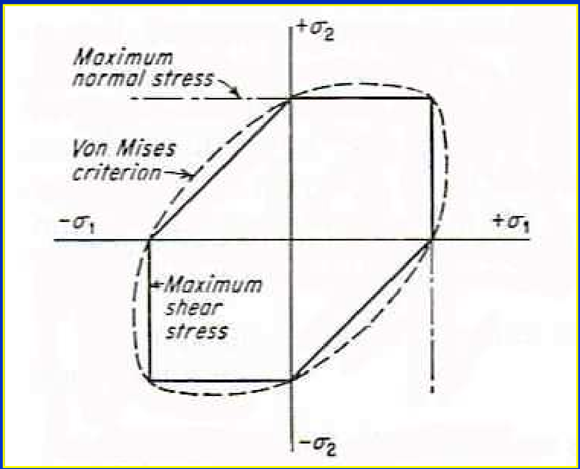
Elastic stresses beneath a notch in thin and thick plates

Effects of combined stress and hydrostatic pressure on fracture

Combined stress

• Yielding under complex states of stress is difficult to predict.

• Available data on ductile metals, i.e., ***Al*** and ***Mg*** alloys and ***steel*** indicate that the ***maximum-shear stress criterion*** for fracture are in the best agreement.

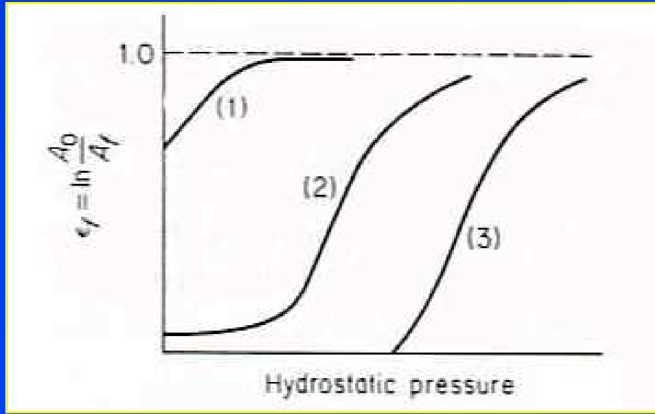


Proposed fracture criteria for biaxial state of stress in ductile metal

Hydrostatic pressure

• ***hydrostatic pressure*** is triaxial compressive stress resist fracture and increase ductility.

• ***Hydrostatic pressure*** exerts no shear stress, it therefore does not influence ***crack initiation*** but affects ***crack propagation***.



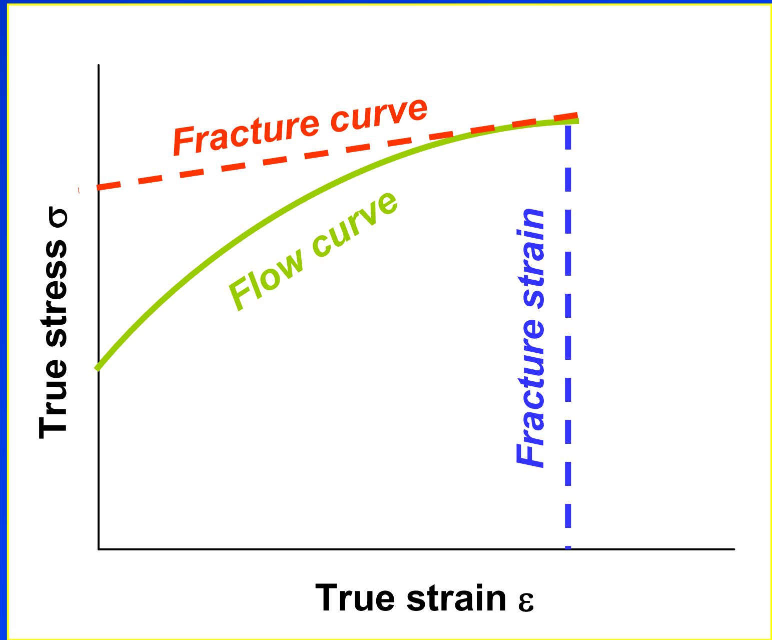
Effect of hydrostatic pressure on ductility in tension

Concept of the fracture curve

Ludwik proposed that a metal has a fracture stress curve in addition to a flow curve (true stress - true strain curve) and that ***fracture occurs when the flow curve intersects the fracture curve***.

- The plastic deformation is inhibited when strain hardening, triaxial stress, or high strain rate, causing sufficiently high stress to break the material.

- ***Fracture stress*** is difficult to measure since most metals exhibit small plastic deformation prior to failure even in the presence of the notch and at very low temperature.

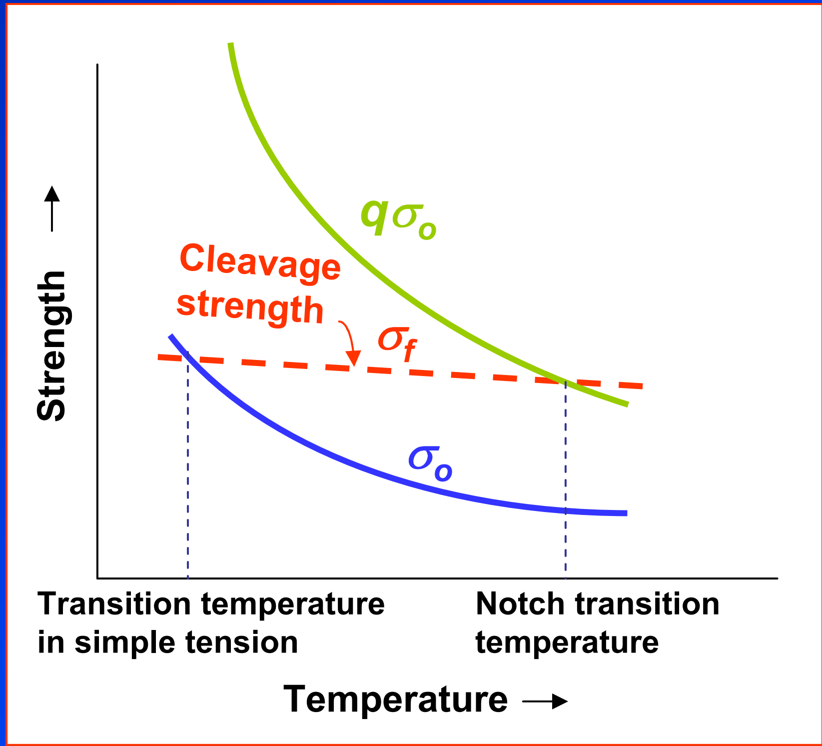


Intersection of flow curve and fracture curve.

Notch effect on transition temperature

The ***fracture stress*** σ_f is much less temperature sensitive than the ***flow stress*** σ_o.

- The σ_o of the ***unnotched specimen*** is lower than σ_f at temperatures above the transition temperature.
- The metal therefore deforms plastically before fracture. Below the transition temperature $\sigma_o > \sigma_f$, metal fails without plastic deformation.
- The ***presence of the notch*** raises the σ_o by the ***plastic-constraint factor q***. This shifts the transition temperature to the right hand side.



Description of transition temperature

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