Fracture mechanics II

Transition temperature and cleavage

Food for thought:

Why cracks are dangerous?

Why cracked component does not break with very small external stress?

What is G? Unit?

What is K? Unit?

How Fracture mechanics is used?

Transition temperature in steels

Transition temperature in steels

Susceptibility to brittle fracture increases with decreasing temperature

At high temperature, brittle fracture not observed

Simple screening criteria to avoid cleavage
=> do not use steels below the transition temperature

Avoid brittle fracture

Conservative

Cost: some steels might work but are excluded

In ferritic steels

At low temperature => brittle cleavage fracture

- Fracture mechanics

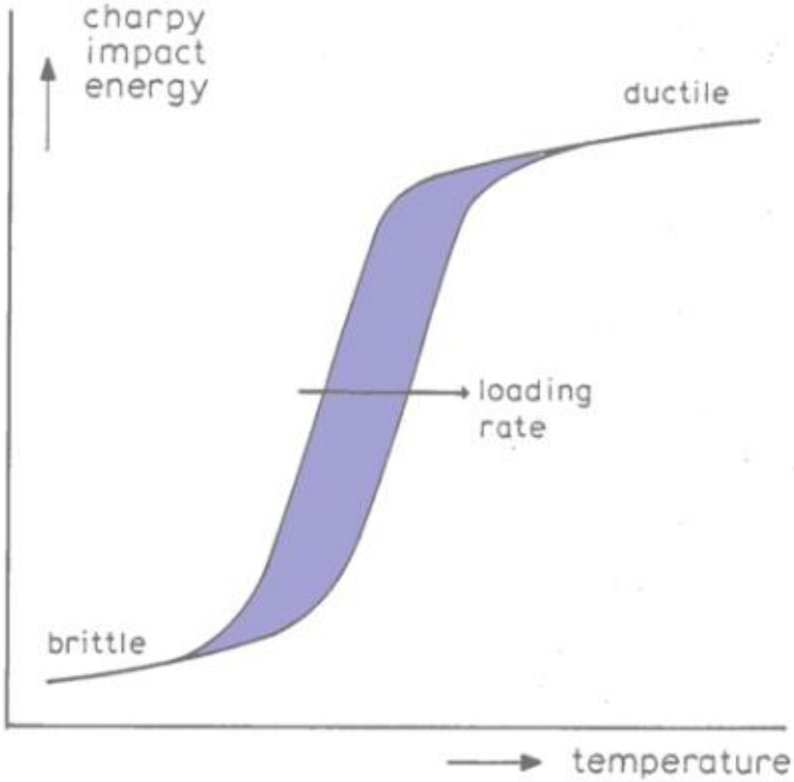
High temperatures => ductile fracture

- design using yield strength

Transition temperature

Above transition temperature, expensive K_{Ic} measurements avoided

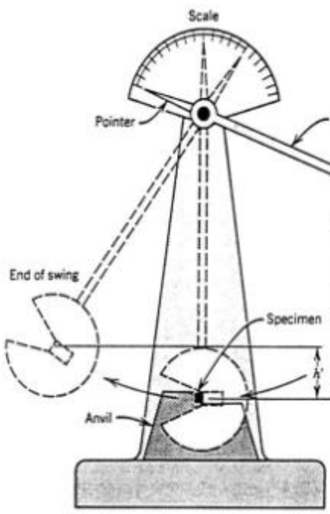
Transition temperature measured by impact testing at different temperatures

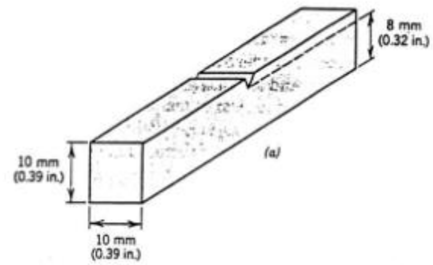


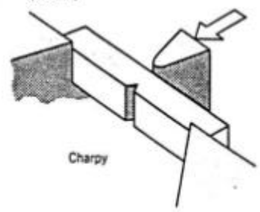
Charpy test

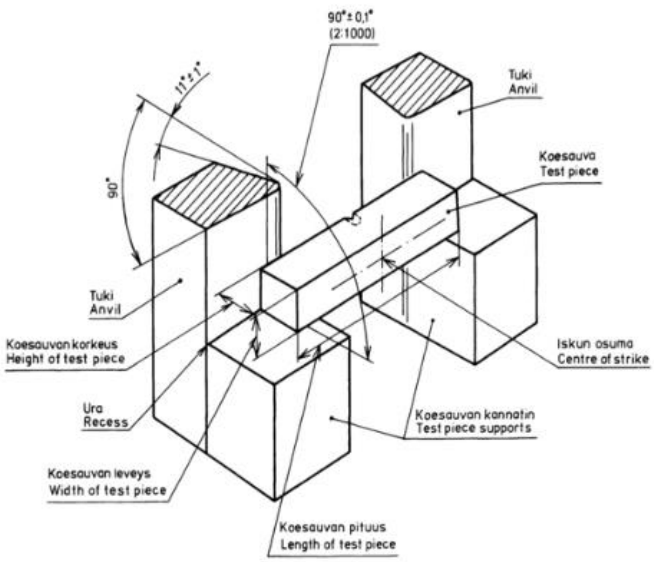
Notched (not cracked) sample
Impact testing
Measure energy of fracture

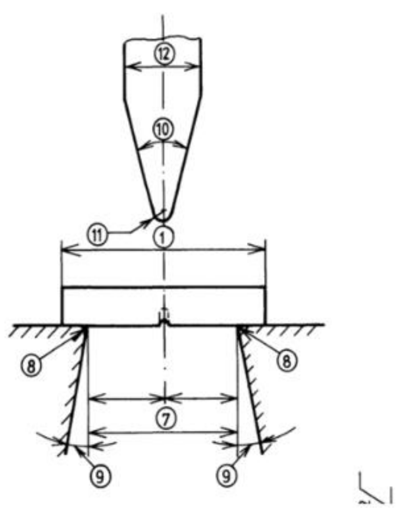
Charpy-V test









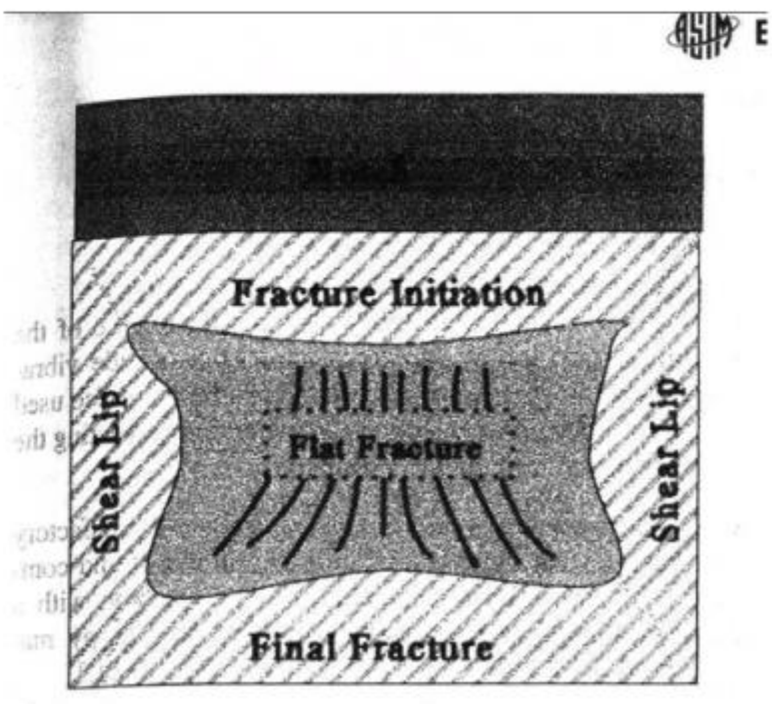


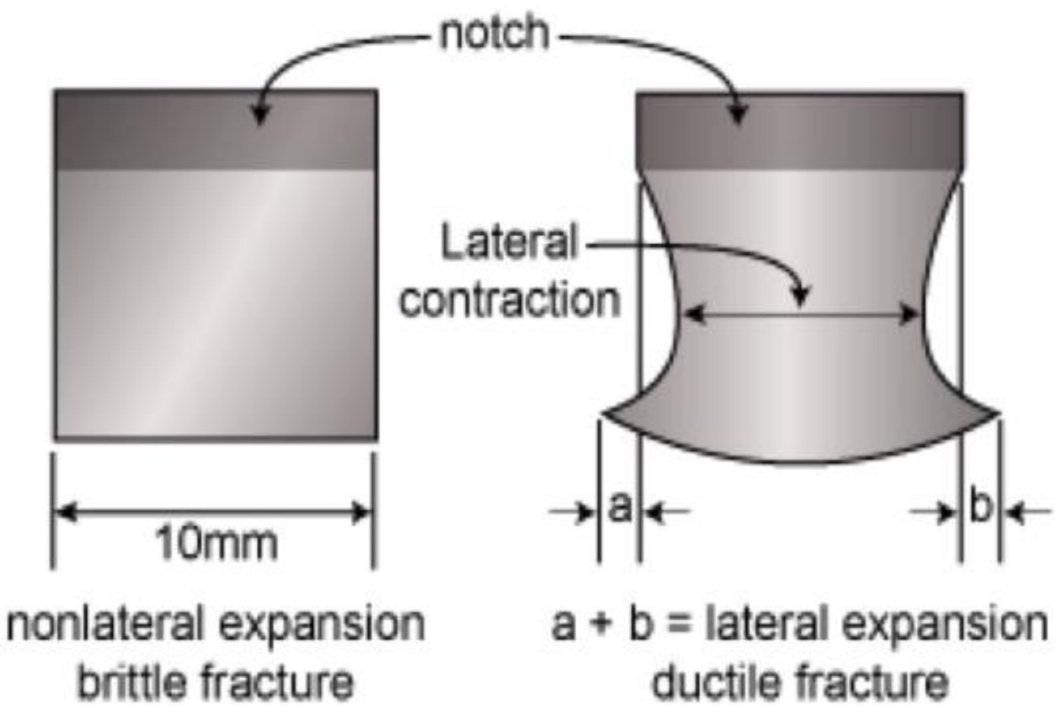
Used in

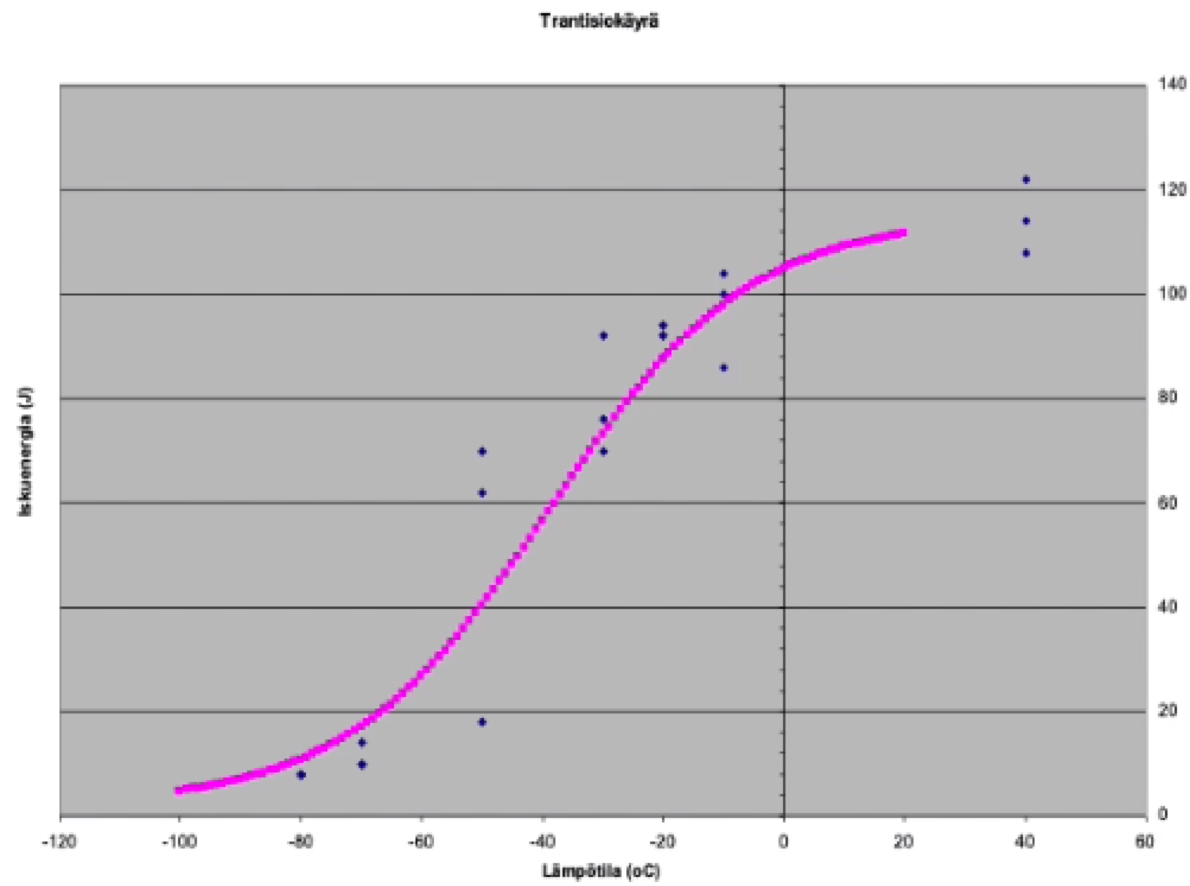
Weld quality control
Thermal treatment quality control (e.g. temper embrittlement)
Screen out embrittlement effects
Transition temperature determination

Transition criteria is one of:

- Dissipated energy 27J (sometimes 40J)
- Fracture surface appearance: 50% ductile fracture
- Lateral expansion




notch
Lateral
contraction
10mm
a
b
nonlateral expansion
brittle fracture
a + b = lateral expansion
ductile fracture

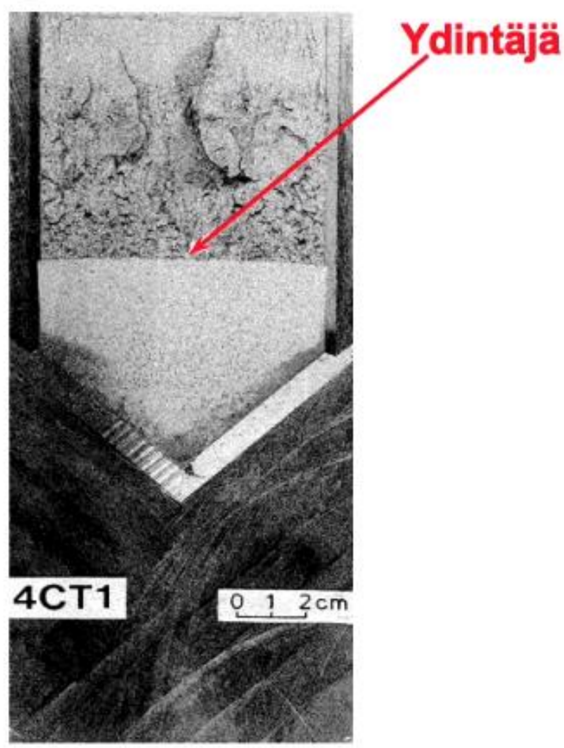

Trantisiokäyrä
Iskuenergia (J)
Lämpötila (oC)
140
120
100
80
60
40
20
0
-120
-100
-80
-60
-40
-20
0
20
40
60

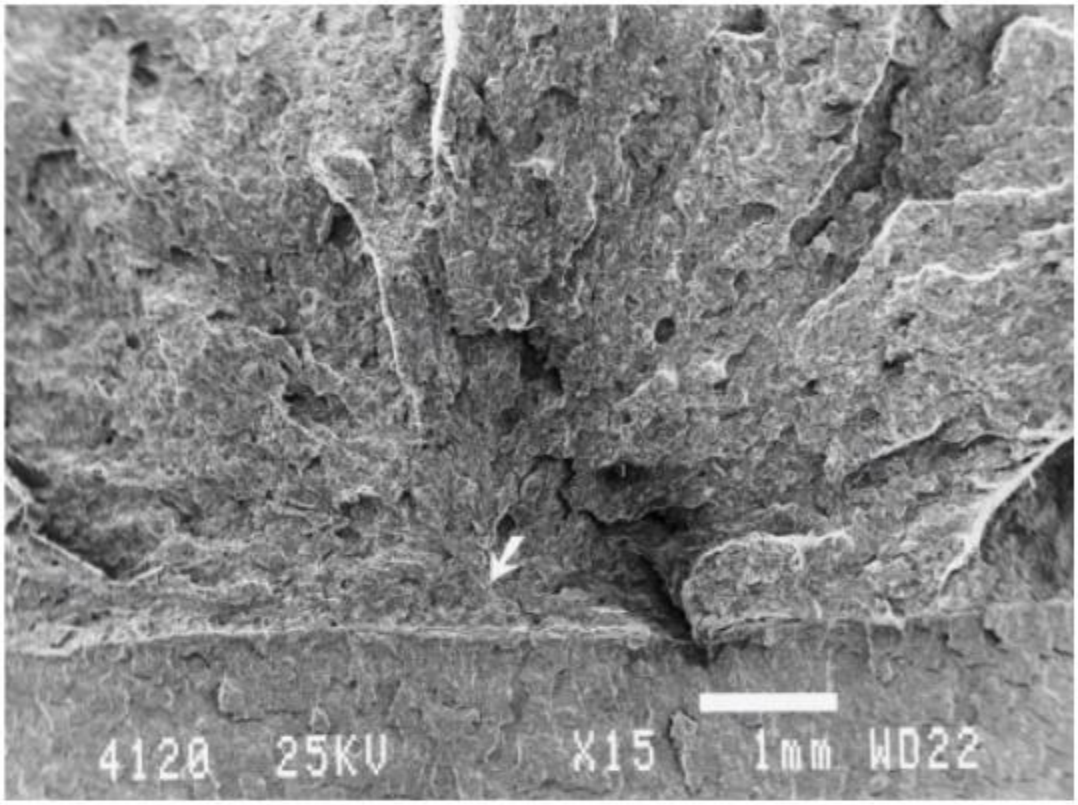
Problems

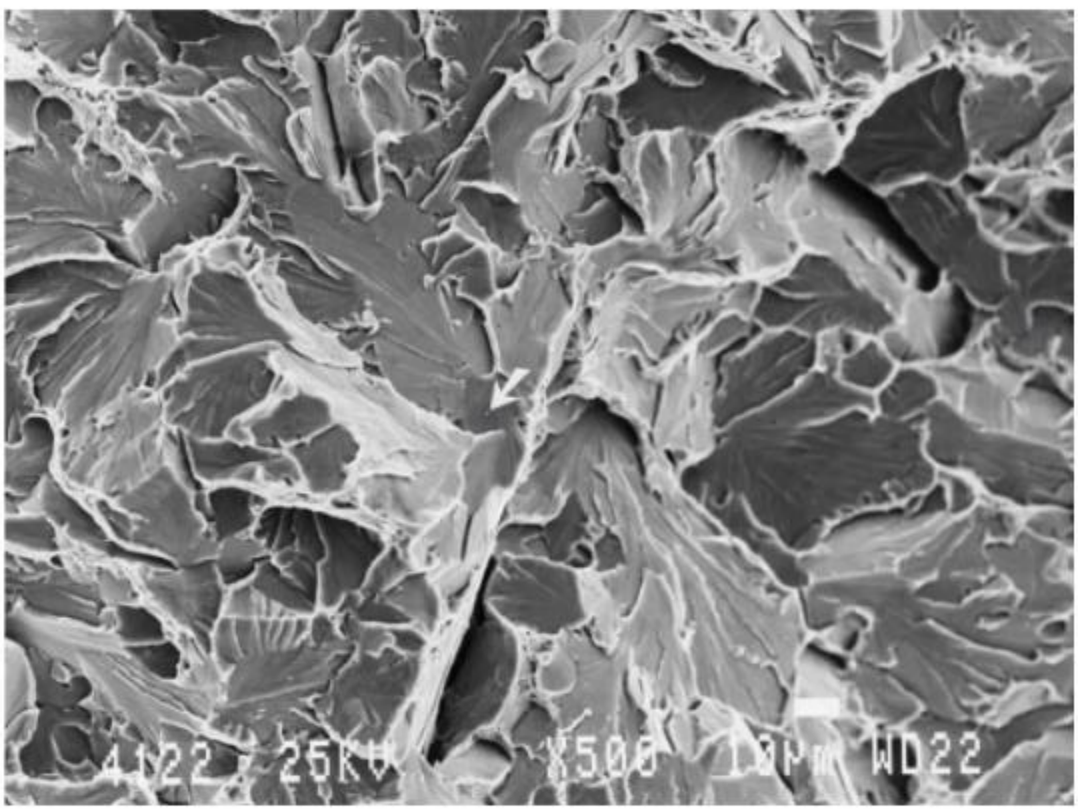
Various criteria for different purposes
No theoretical basis
Unnecessarily restrictive

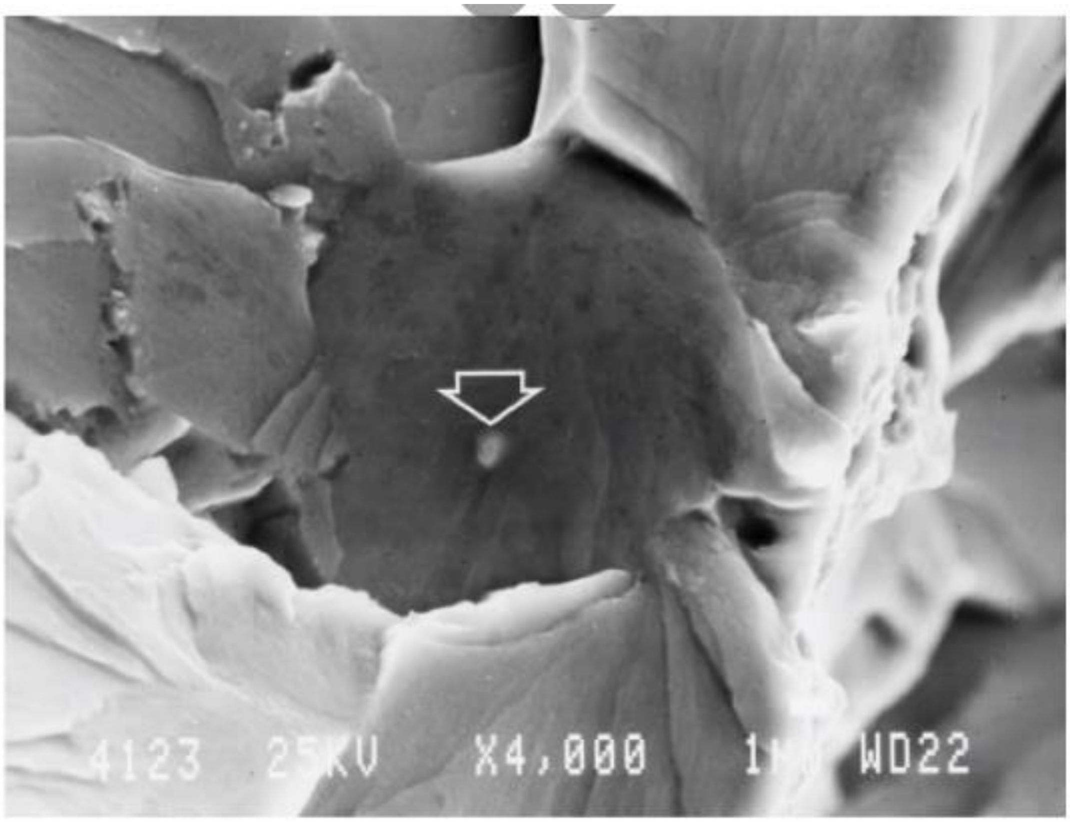
Cleavage fracture

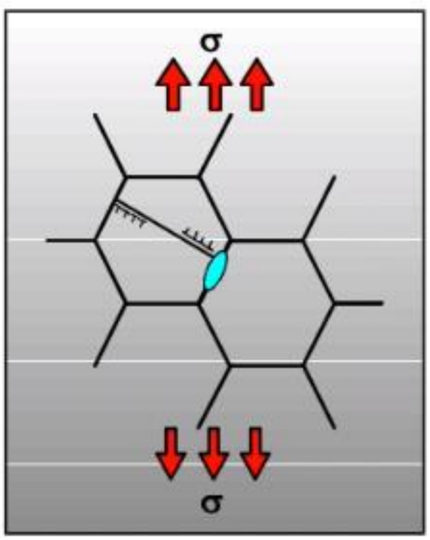
A508 Cl.3
T = - 30° C
K_{JC} = 280 MPa√m
Δa = 0.1 mm



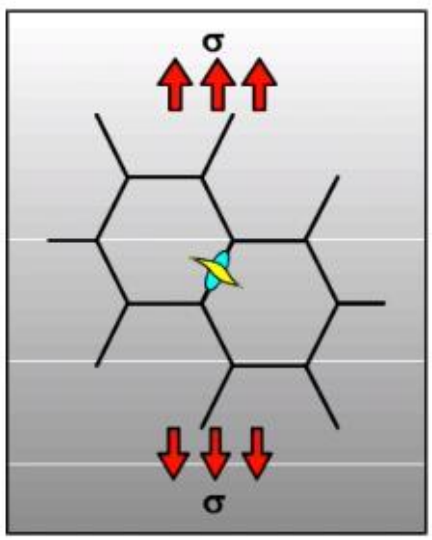

4120 25KV X15 1mm WD22


4122 25KV X500 10Pm WD22

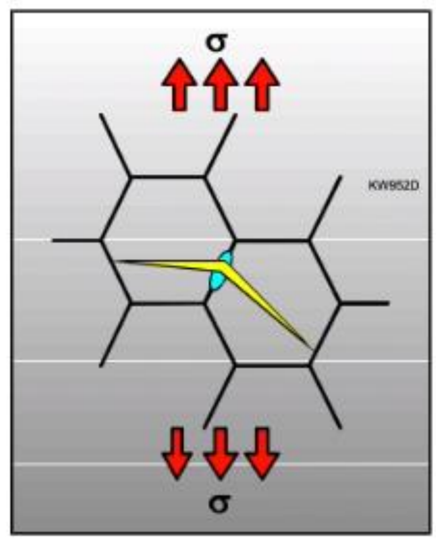




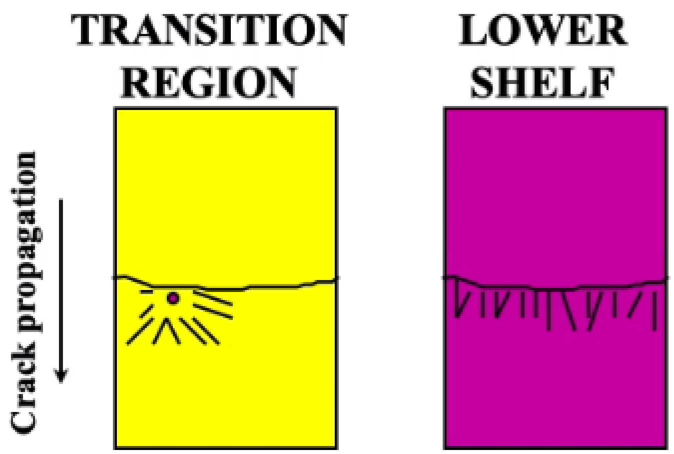
Local stress produces a dislocation pile-up which impinges on a grain boundary carbide.



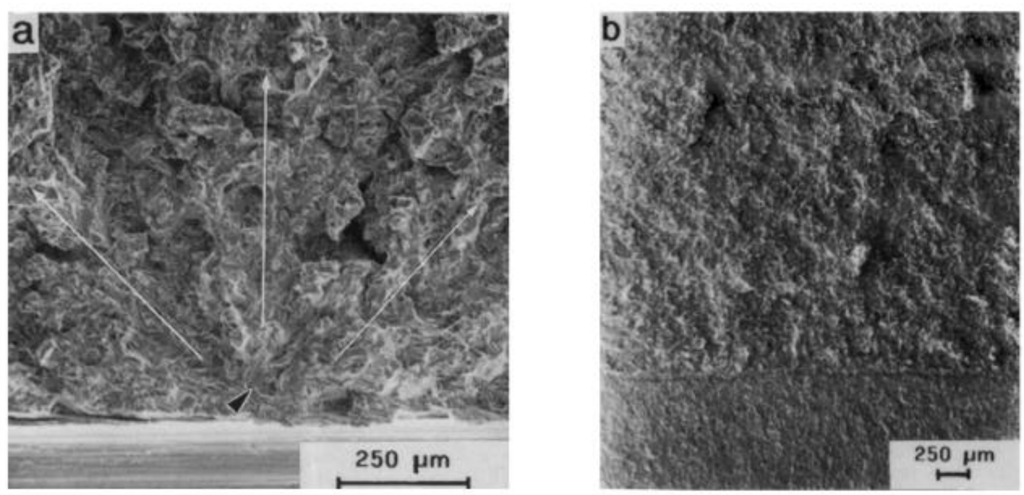
Cracking of the carbide introduces a microcrack which propagates into the matrix.



Advancing microcrack encounters the first large angle boundary.



FRACTURE SURFACES AT 77K



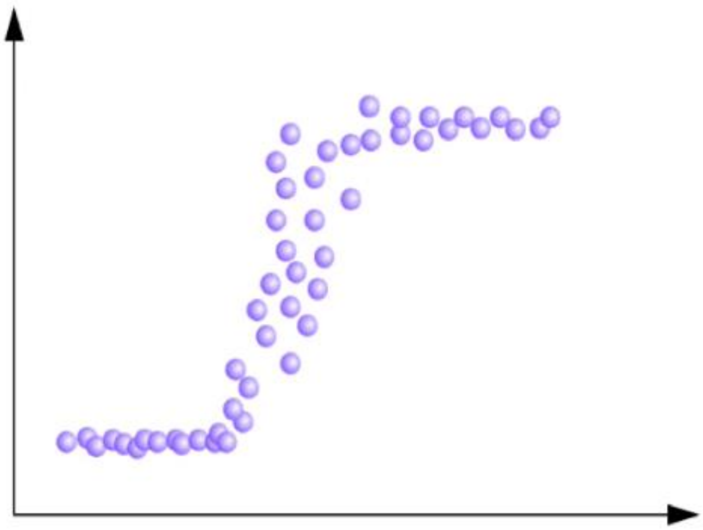
BLUNT-NOTCHED SPECIMEN

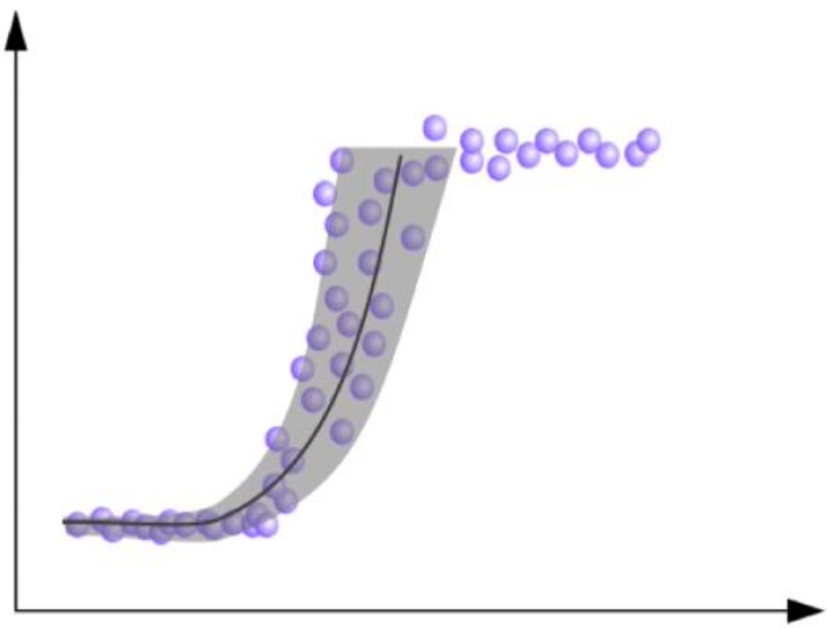
FATIGUE PRECRACKED SPECIMEN

Cleavage fracture initiation

Stochastic in nature
Size effect
Limited by crack growth (size of tip singularity)
Possible ductile tearing before cleavage fracture

Closer look





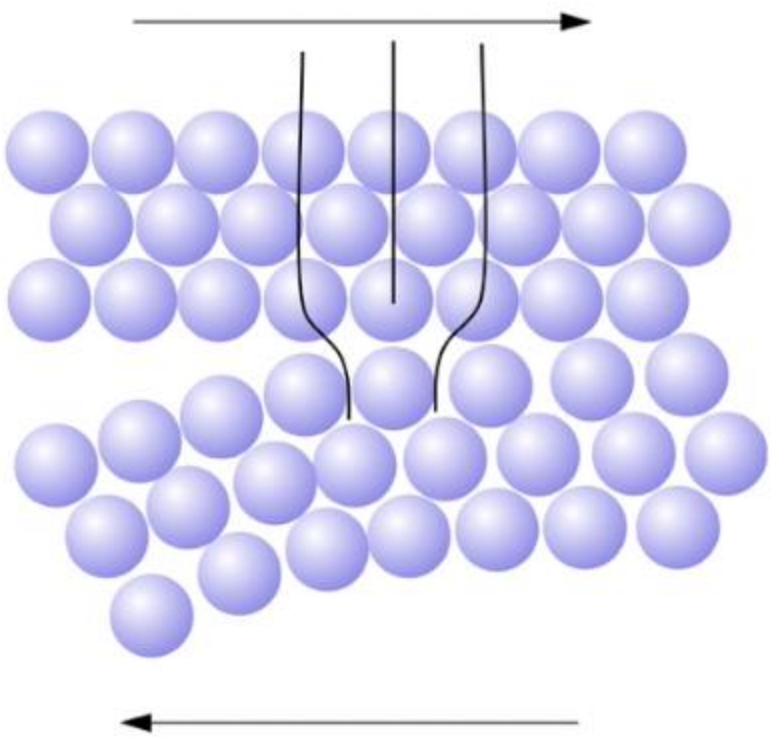
Why?

- ferritic steels are susceptible to cleavage fracture?
- transition temperature (= strong temperature dependence of cleavage fracture)
- impact loading promotes cleavage?

Cleavage fracture – simplified atomistic look

In continuum-material crack tip has infinite stresses

In real materials crack tip is never zero due to material discontinuities and plastic deformation



At crack loading, atoms move to peiers potential maximum, and either

- dislocation forms and decreases stress
- crack grows

Selection determined by energy balance; lower energy mechanism prevails

(simplified explanation)

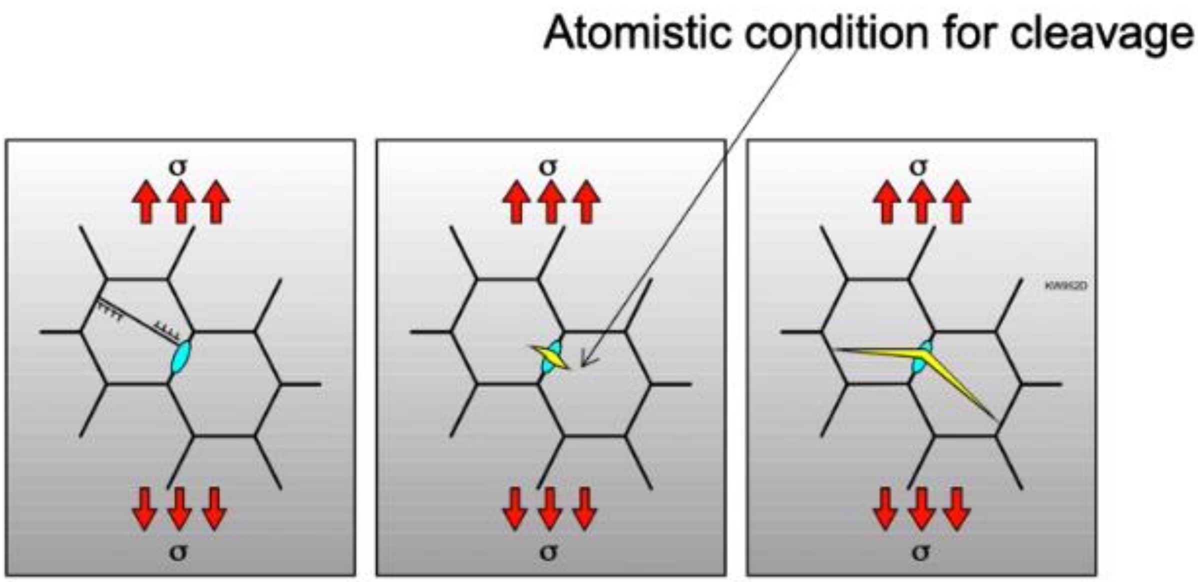
Transition temperature

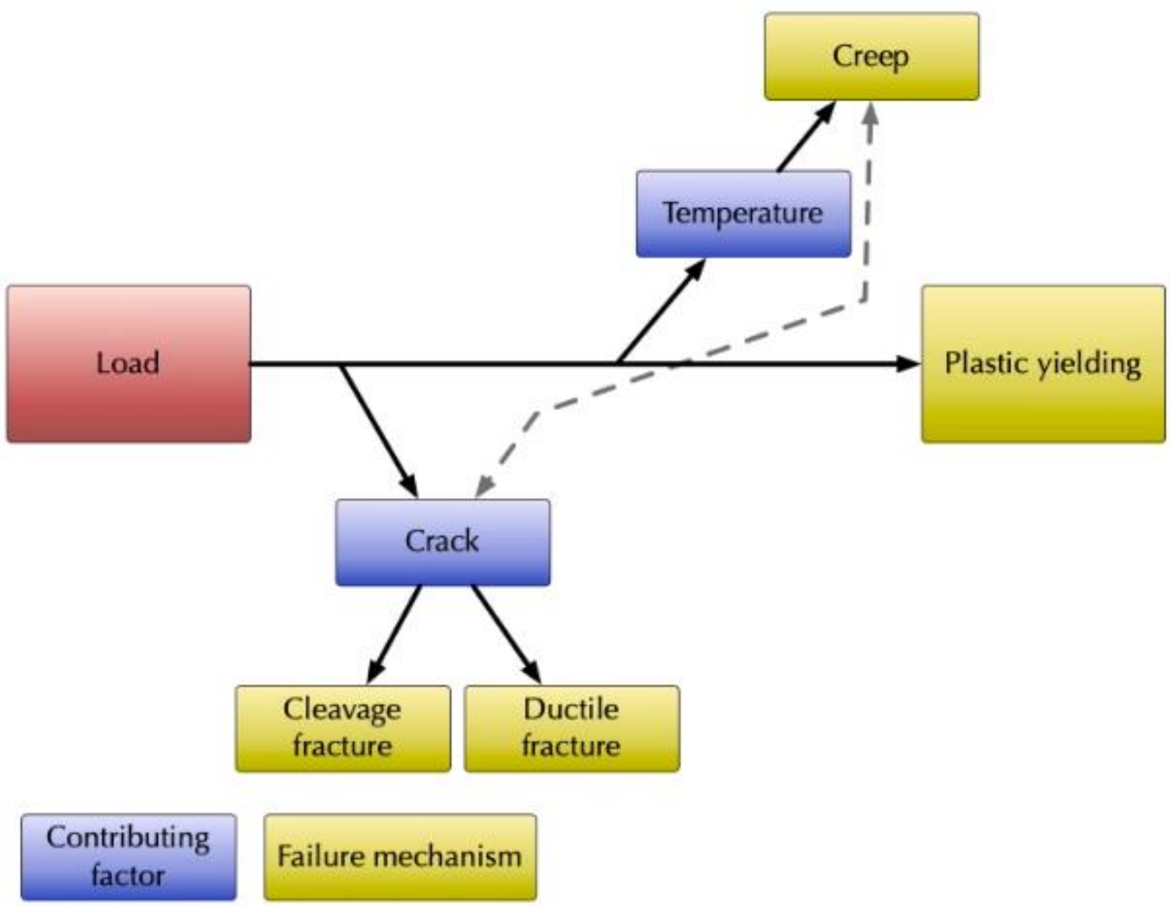
Whatever decreases surface energy or increases dislocation energy makes cleavage more likely

Decrease in temperature for BCC materials

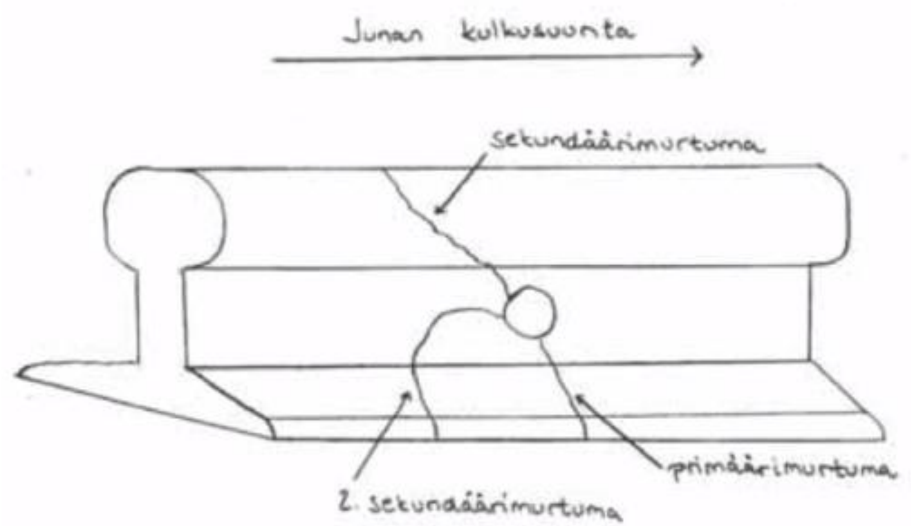
High loading rate for BCC materials

[fracture energy decreases with decreasing temperature in other materials as well, but there's no mechanism-transition]


Atomistic condition for cleavage
σ
σ
σ
σ
σ
σ


Creep
Temperature
Load
Plastic yielding
Crack
Cleavage fracture
Ductile fracture
Contributing factor
Failure mechanism

Rail fracture- revisited



Kuva 6. Skemaattinen esitys primääri- ja sekundäärimurtumien sijainnista toisiinsa nähden.

Data

Rail in use for 30 years

Cleavage initiated in badly finished hole

0.9 mm initial crack found

Low impact energy measured (<10J)

Low K_{Ic} measured

Measured values are like those in new rail

The ground under the rail had softened - increased load

Big residual stresses measured

Rails under tension at the prevailing temperature (-7° C, neutral temperature at +15° C)

Failure investigation conclusions

Immediate cause was rail failure under train wheelset. Previous fracture initiated failure.

Failure *probably* caused by bad finishing in attachment hole and local rail properties.

Additional contributing factors: rail residual stresses, prevailing tensile stress and land softening under the rail

The initiating fracture was noted by excessive noise by two previous trains, but it's seriousness went underestimated and thus led to failure and derailing.

Mooring chain failure

Engineering Failure Analysis 17 (2010) 1542–1550

Contents lists available at ScienceDirect

Engineering Failure Analysis

ELSEVIER

journal homepage: www.elsevier.com/locate/engfailanal

Failure analysis of Grade-80 alloy steel towing chain links

Khaled Al-Fadhalah *, Ahmed Elkholy, Majed Majeed

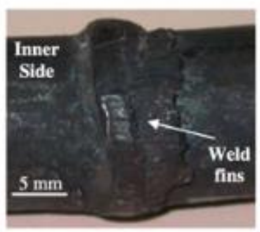
Department of Mechanical Engineering, College of Engineering and Petroleum, Kuwait University, P.O. Box 5969, Safat 13060, Kuwait

Failure

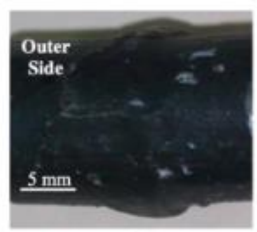
Heavy mooring chain was used daily to tow military vehicles
Chain broke during towing (potentially dangerous)
Chain had seen little use prior to failure

Failure initiated at weld

(a)



(b)



(c)

Heavy chain, should take 322 kN

Table 1
ASTM A391 standard specifications of Grade-80 alloy steel chain for $d = 16$ mm.

Nominal chain size (mm)	Material diameter (mm)	Working load limit (kN)	Proof load limit (kN)	Minimum breaking force (kN)	Inside length l_i (mm)	Inside width w_i (mm)
16.0	16.0	82	161	322	51.2 (max)	24.0 (max)

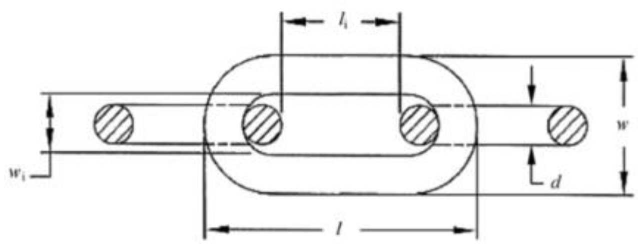


Fig. 2. Geometry and dimensions of Grade-80 alloy steel chain used in this study ($d = 16$ mm, $l_i = 48.8$ mm and $w_i = 25.9$ mm).

Yield and UTS according to specification

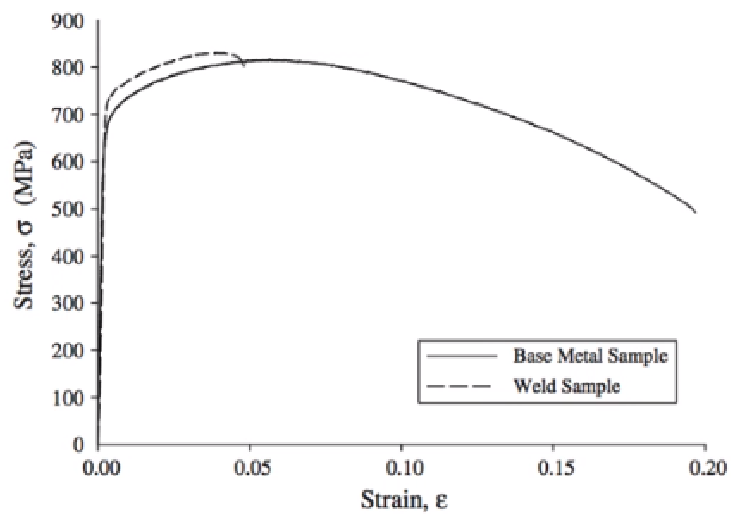
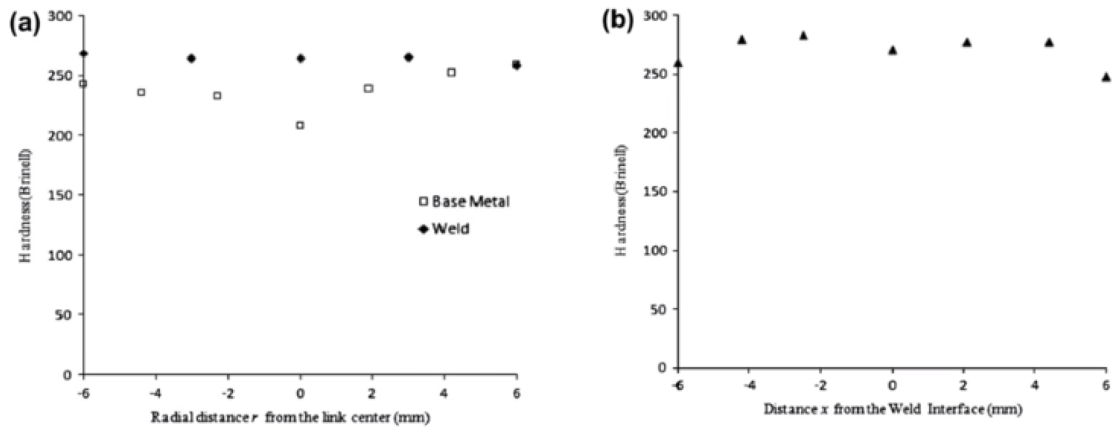


Fig. 4. Tensile stress–strain behavior of the Grade-80 steel chain (base metal and weld).

Hardness OK



Initial cracks in the weld

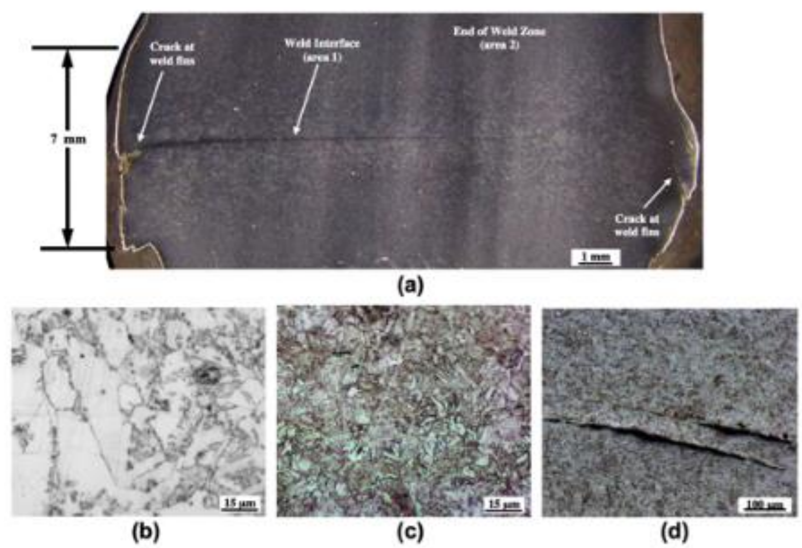
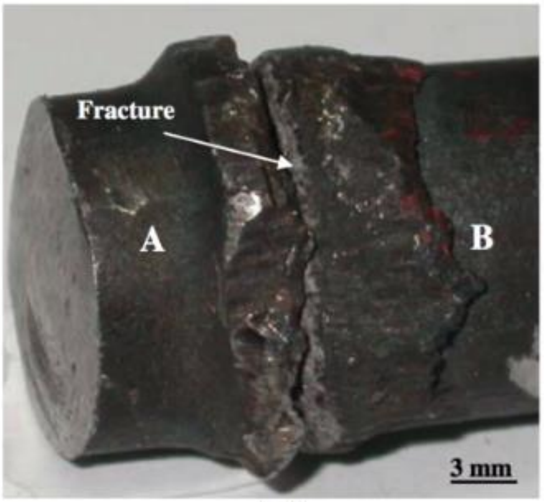


Fig. 6. Optical microscope photographs show: (a) microstructure of unused chain link at the weld, (b) microstructure of "area 1"at the weld interface, (c) microstructure of "area 2" presenting quenched and tempered martensite and (d) presence of internal cracks found in different areas inside the weld.

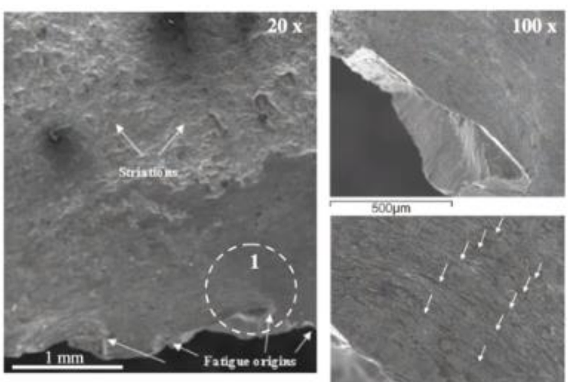
Fracture surface shows, fatigue, cleavage and ductile fracture



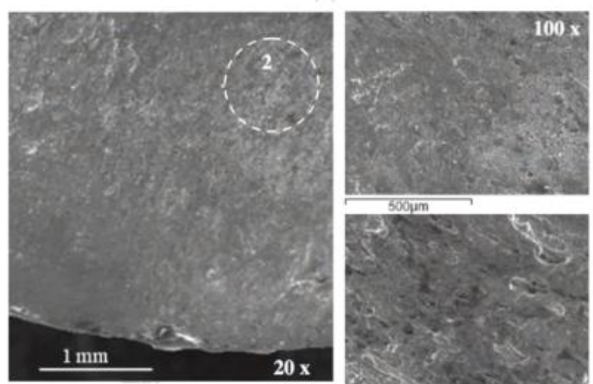
(a)

(b)

Fracture surfaces badly worn due to contact



(a)



(b)

Contributing factors

Material composition not quite to specification => lessened hardenability

Weldment included initial cracks and brittle areas

Cyclic loading

Overloading

Root cause

Poor weld quality and initial flaws caused by it enabled fatigue and finally during a single overload, final fracture

Aalto-yliopisto
Insinööritieteiden
korkeakoulu

LEFM ⇒ EPFM

LEMF Limitations

K is valid, when

- plastic deformation is limited to small area around the crack
- measured at plain strain conditions
- ⇒ for brittle materials

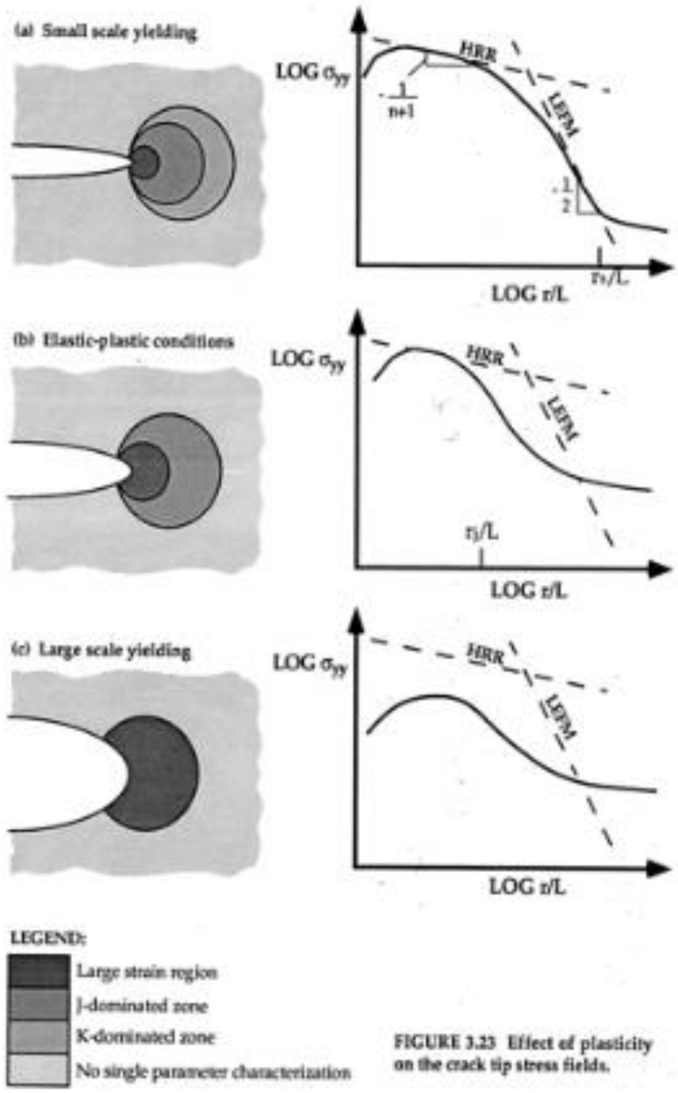


FIGURE 3.23 Effect of plasticity on the crack tip stress fields.

Validity

Standard (ASTM) requirements:

r_y < specimen size / 50

$$a, B, (W - a) \geq 2.5\left(\frac{K_I}{\sigma_{YS}}\right)^2$$

- Plain strain

LEFM valid, as long as singularity dominated zone is small compared to other dimensions

- Or => test with full material thickness

Singularity dominated fracture

As long as fracture happens in small area of possible plasticity confined to the singularity dominated zone, the fracture conditions are enclosed in the singularity and LEFM can be used.

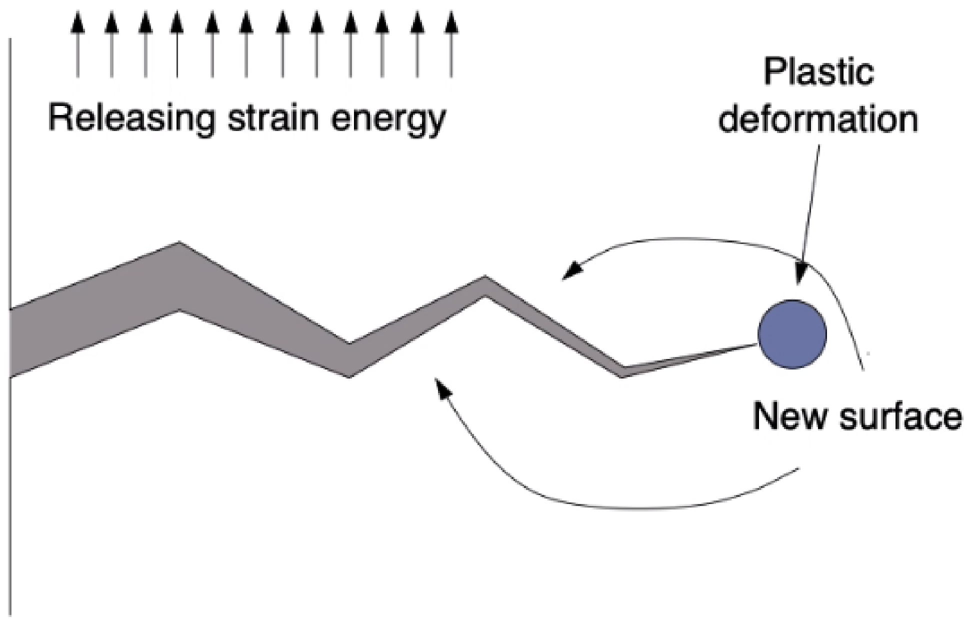
For more ductile materials:

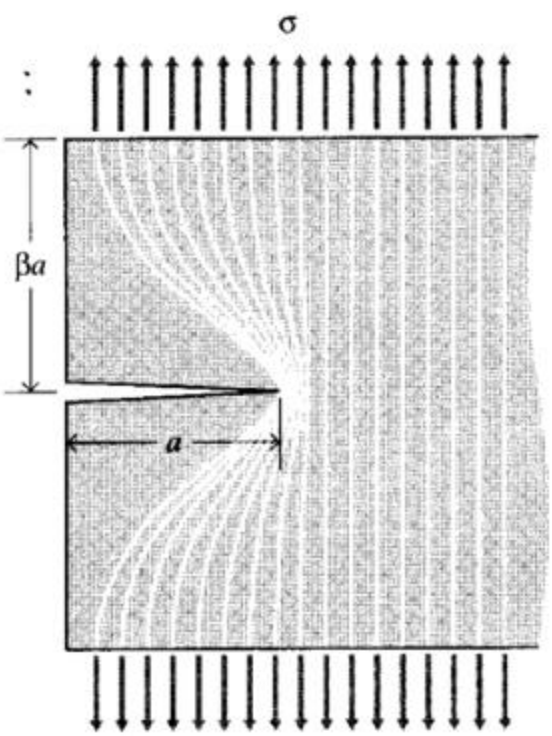
Crack tip plasticity increases

Crack tip blunts

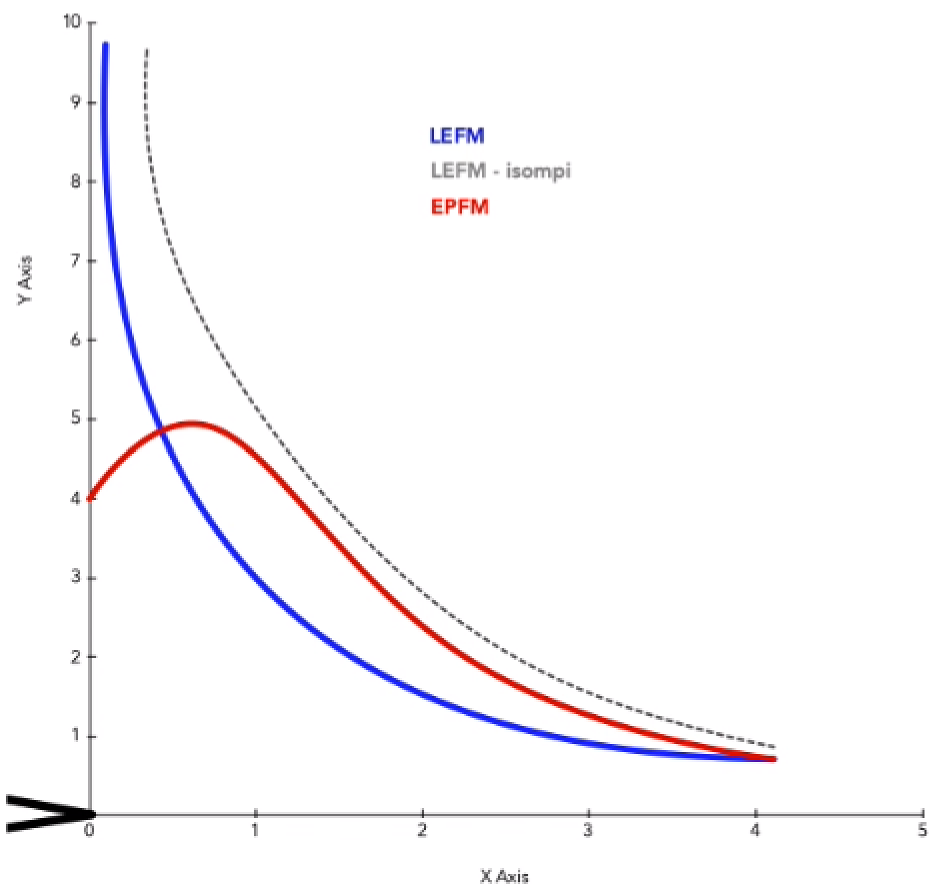
Crack may have ductile crack growth before final fracture

Blunting effect





σ
βa
a



LEFM
LEFM - isompi
EPFM
Y Axis
X Axis

Plastic zone size ~ distance, where stress exceed yield strength (first approximation)

$$r_p = \frac{1}{\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2$$

Irwinin plasticity correction

Solution has error, because it's based on elastic material

- Yielding caused stress redistribution to attain balance
- Introducing correction by balancing equation yields:

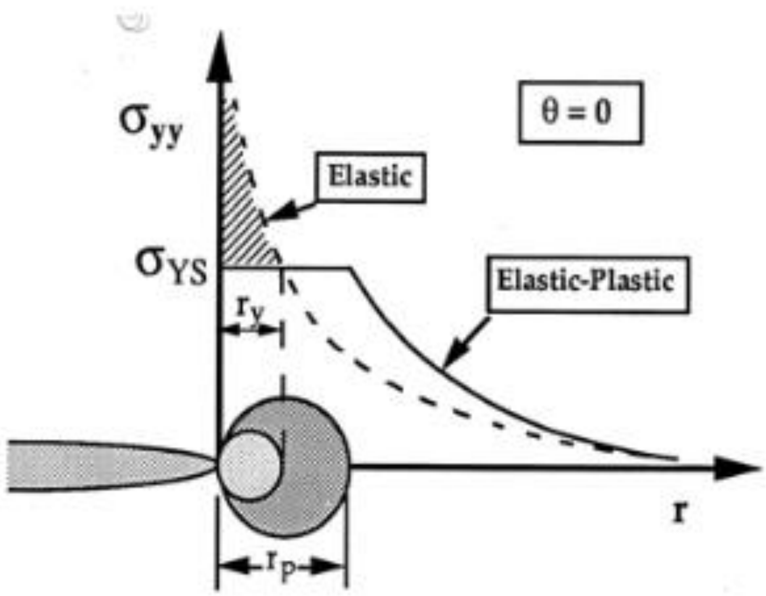
$$r_y = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2$$

Irwinin correction: crack behaves as if tip is in the middle of the plastic zone

K_{eff} depends on K => iterative solution

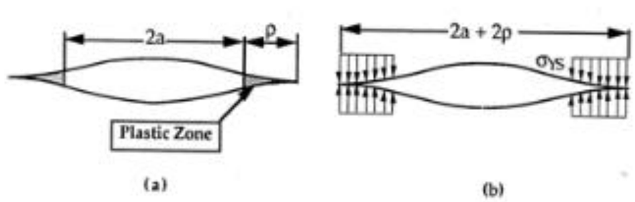
$$a_{eff} = a + r_y$$

$$K_{eff} = Y(a_{eff})\sigma\sqrt{\pi a_{eff}}$$

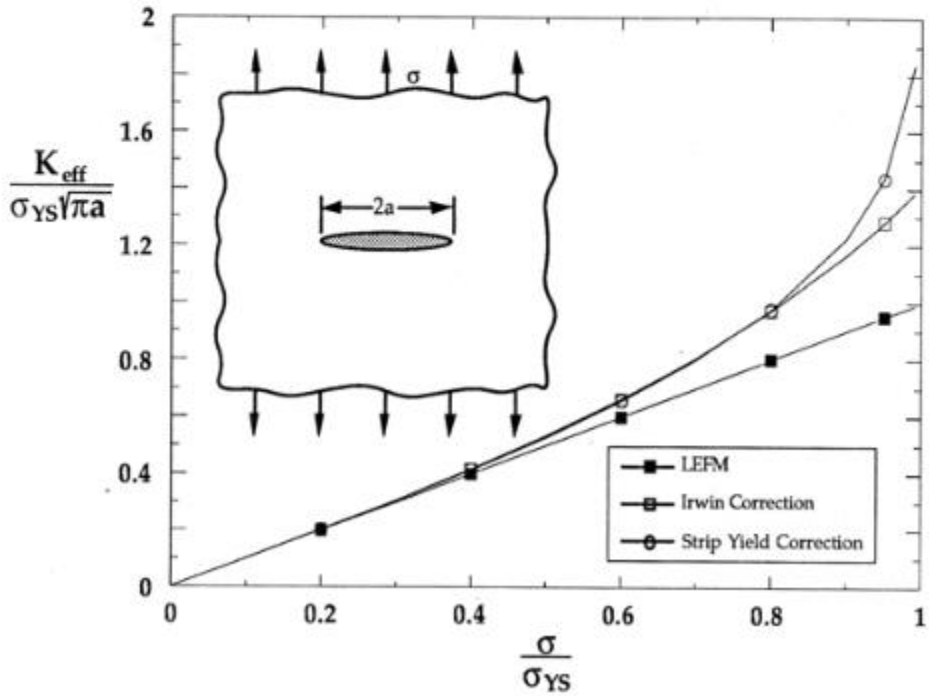


Duddale - Barenblatt

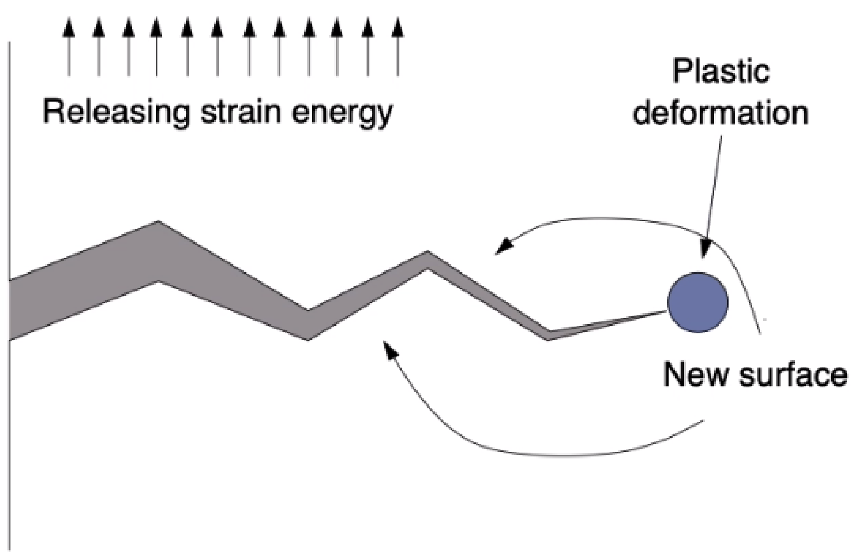
Strip-yield model

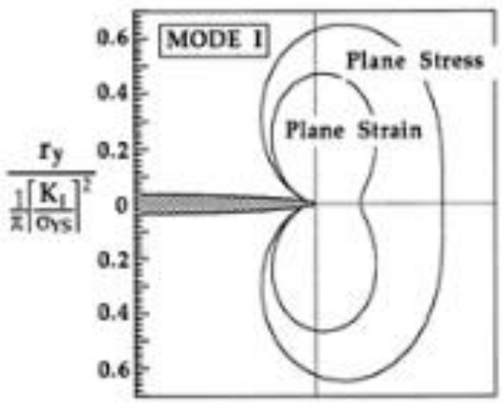


$$K_{eff} = \sigma_{YS}\sqrt{\pi a}\left(\frac{8}{\pi^2}\ln sek\left(\frac{\pi\sigma}{2\sigma_{YS}}\right)\right)^{\frac{1}{2}}$$

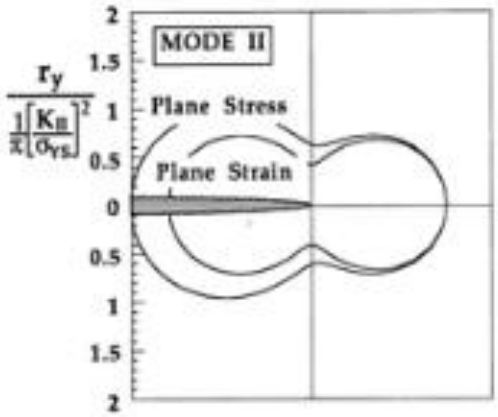


Fracture balance

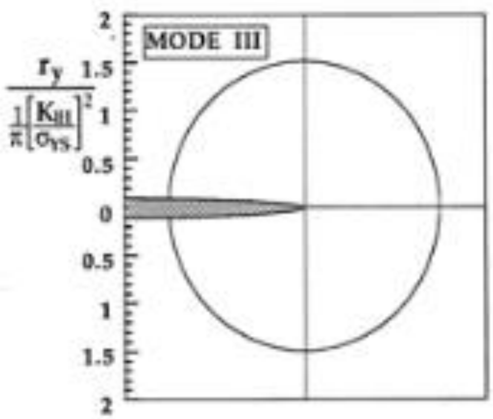




(a) Mode I



(b) Mode II



(c) Mode III

FIGURE 2.31 Crack tip plastic zone shapes estimated from the elastic solutions (Tables 2.1 and 2.3) and the von Mises yield criterion.

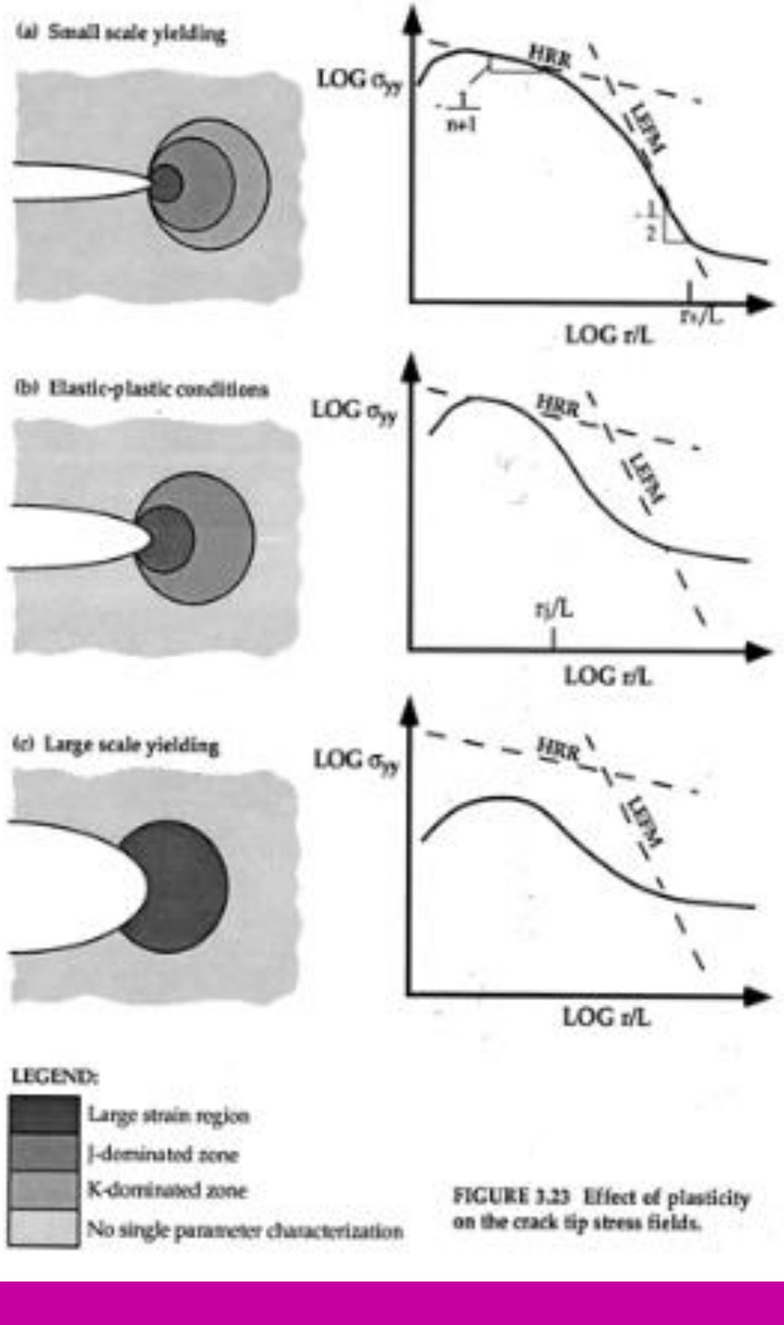


FIGURE 3.23 Effect of plasticity on the crack tip stress fields.

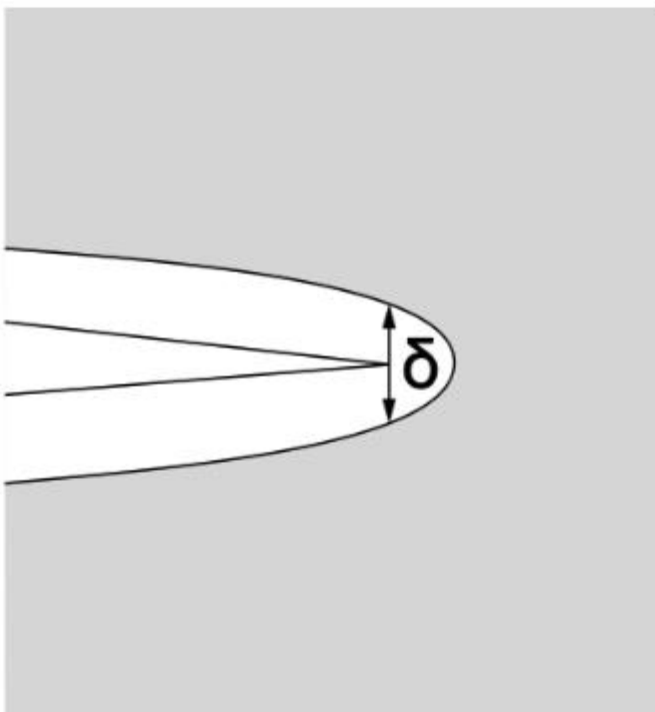
Elastic-plastic fracture mechanics (EPFM)

CTOD

Wells - K_{Ic} values can not be measured for more ductile materials

The more ductile materials are, more blunting is observed prior to fracture

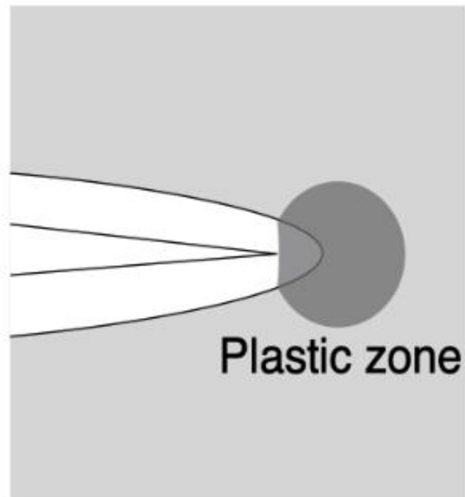
Use crack tip blunting (i.e. crack tip opening displacement) as a measure of ductility



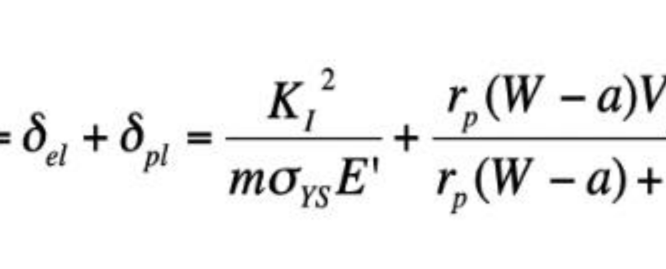
CTOD

Related to K in LEFM conditions

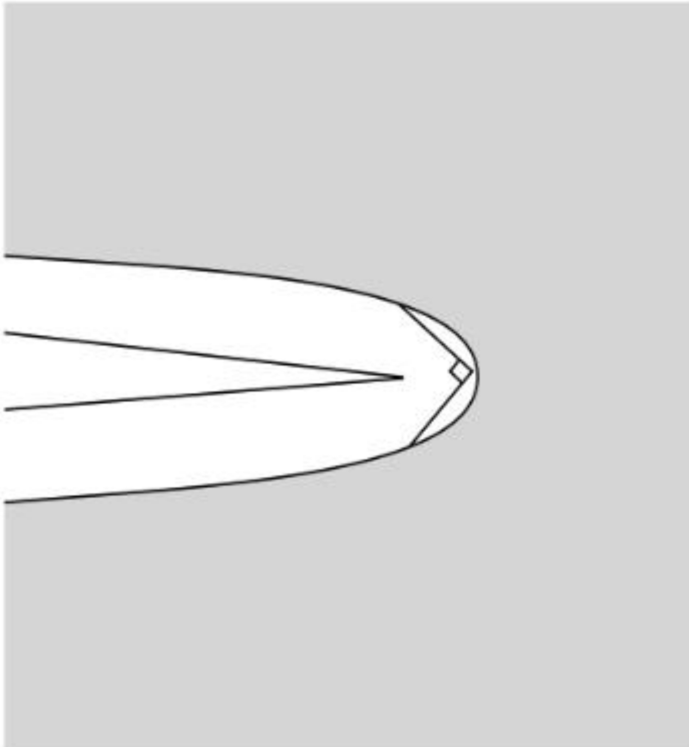
$$\delta = \frac{4}{\pi}\frac{K_I^{\ 2}}{\sigma_{YS}E}$$



Experimental measurement



$$\delta = \delta_{el} + \delta_{pl} = \frac{K_I^{\ 2}}{m\sigma_{YS}E'} + \frac{r_p(W-a)V_p}{r_p(W-a)+a}$$



J-integral

Nonlinear G

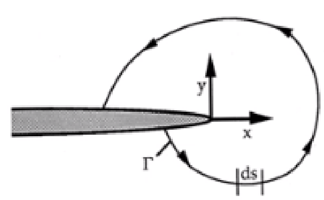
$$J = -\frac{d\Pi}{dA} = U - F$$

Path independent integral IF

- no internal stresses or
- thermal variations

(then area-term added)

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$



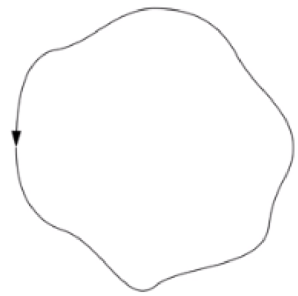
Path independence

J is Stress-potential integral

T_i is stress in direction of the line normal

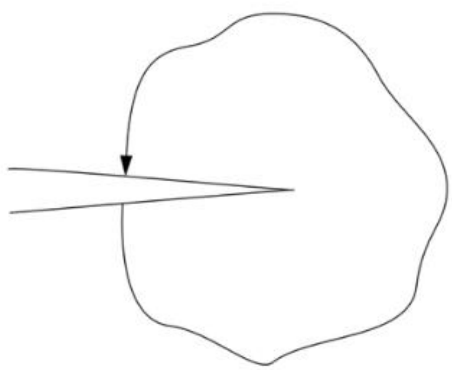
Integral around arbitrary closed loop is 0

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$



$J = 0$

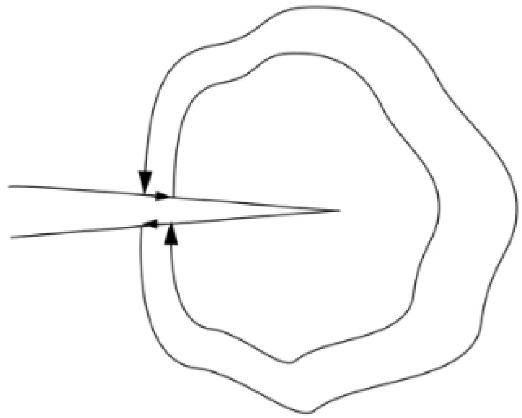
Across crack tip J≠0



$J \neq 0$

Path independence

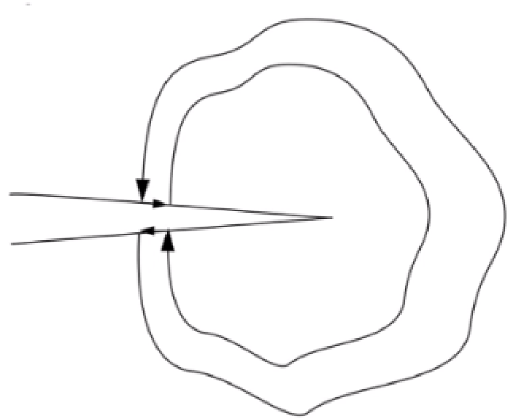
Closed loop J1+J2+J3+J4 :
J2 = J4 = 0
T_i = 0 at free surface
J1 = -J3 at arbitrary J3
=> J is path independent



$$J1+J2+J3+J4 = 0$$

Path independence

Closed loop J1+J2+J3+J4 :
J2 = J4 = 0
T_i = 0 at free surface
J1 = -J3 at arbitrary J3
=> J is path independent



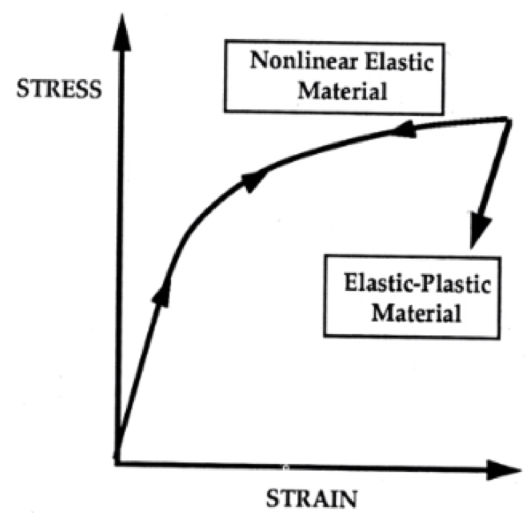
$$J1+J2+J3+J4 = 0$$

J describes crack properties

$$J = -\frac{d\Pi}{dA}$$

J-integraali

LEFM extension by modeling elastic-plastic as nonlinear-elastic



G and J

At linear elastic region G = J

J valid for nonlinear-elastic region

Monotonically increasing loading does not distinguish between elastic-plastic and nonlinear elastic

J describes material loading beyond G:s validity range

Energy release and driving force

"Energy release rate" is to be taken as change in energy balance caused by small incremental crack growth

J-integral as stress parameter

J describes uniquely crack tip stress conditions

Describes crack tip stress state

- HRR singularity
- LE => $$\frac{1}{\sqrt{r}}$$
- EP => $$r^{-\frac{1}{n+1}}$$

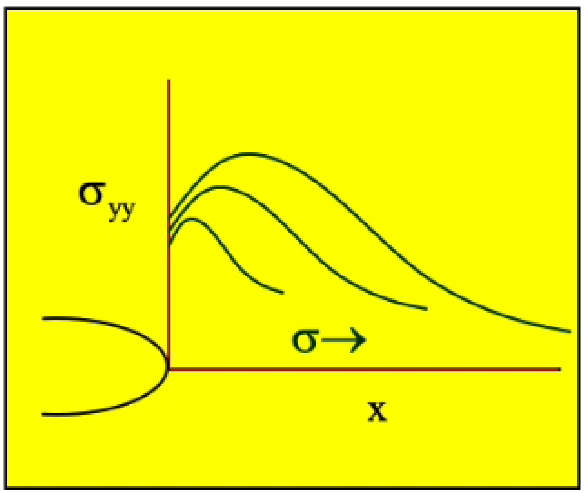
Crack tip singularities

LEFM region has stress singularity, which describes crack tip conditions, when plasticity is small and confined to small area around crack tip

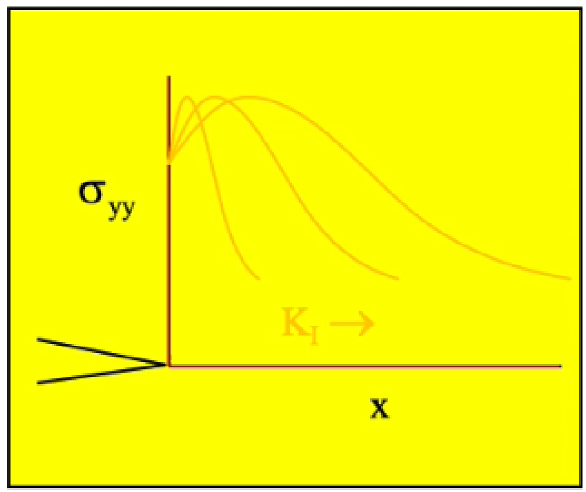
Bigger loading (blunting), HRR singularity prevails and describes crack tip conditions as long as plasticity is confined to ara near crack tip

HRR-singularity breaks down as general yielding approaches

Lovi



Särö

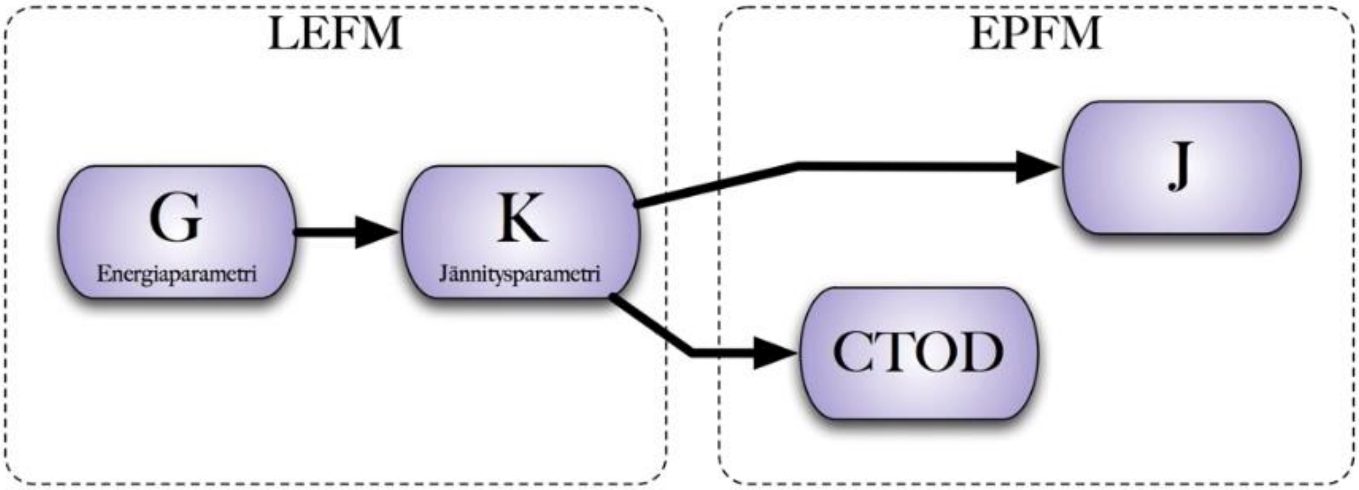


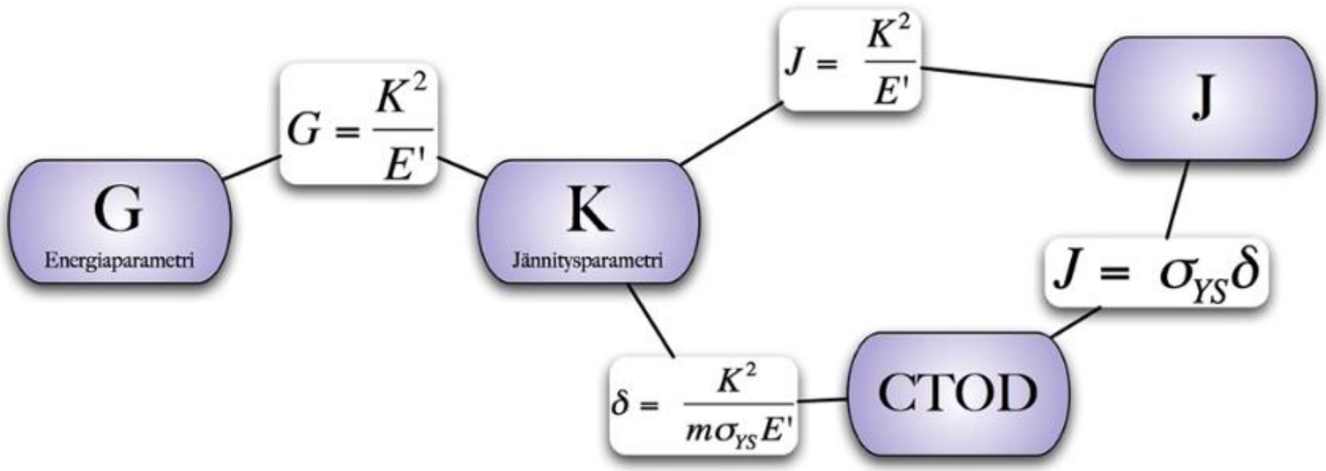
J vs CTOD

$$J = \sigma_{YS}\delta$$

K - J

K and J related in LE-conditions
In EP-conditions, and "equivalent K" can be computed
We can measure J with small samples and compute K
=> K_{Jc}





Similitude

(Any) one parameter is enough

A fracture mechanics parameter (G, K, J tai CTOD) alone is sufficient to describe fracture susceptibility (where it's valid)

Regardless of loading, crack size, geometry, material, environment, etc.

"Silimitude concept"

LEFM or EPFM

LEFM	EPFM
Measurement expensive	Measurement easier
Analysis simple	Analysis complicated (requires elastic-plastic FEM, in practice)

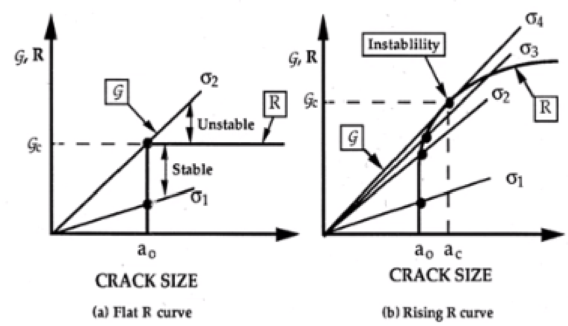
Ductile fracture

Ductile fracture

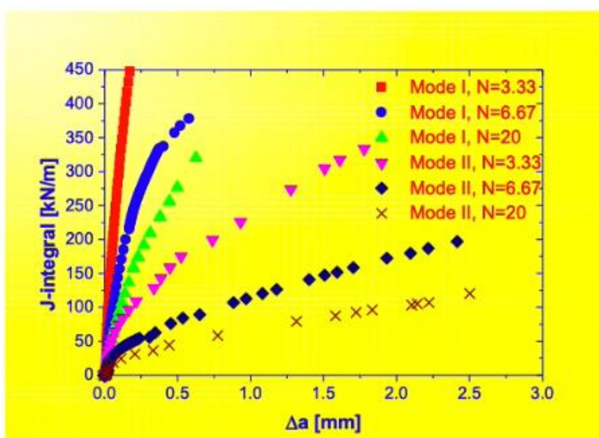
Void nucleation
Void growth
Void coalescence

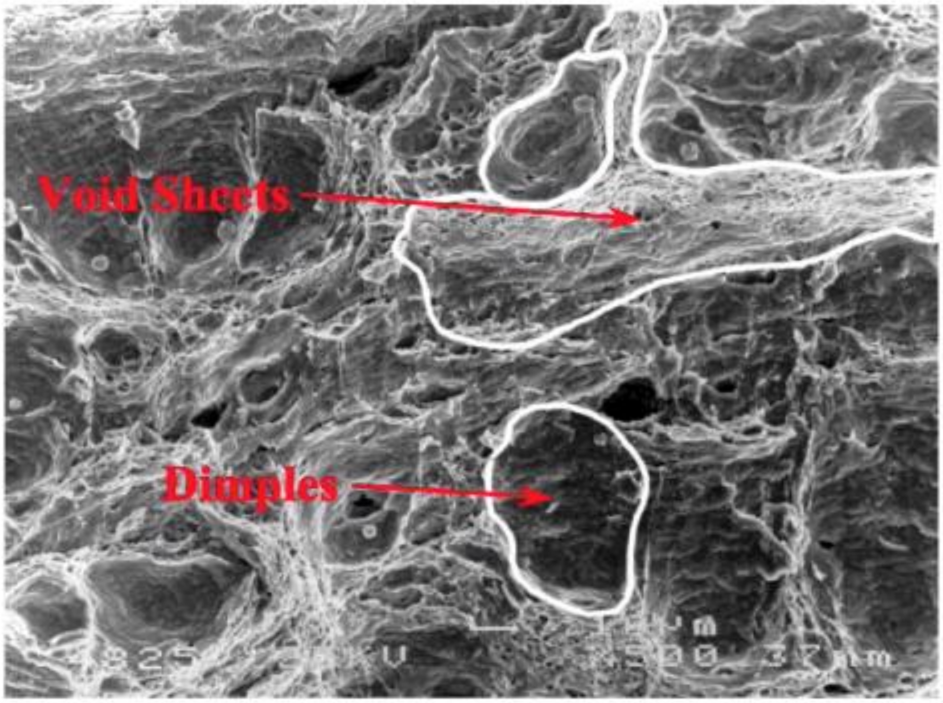
J-R -curve

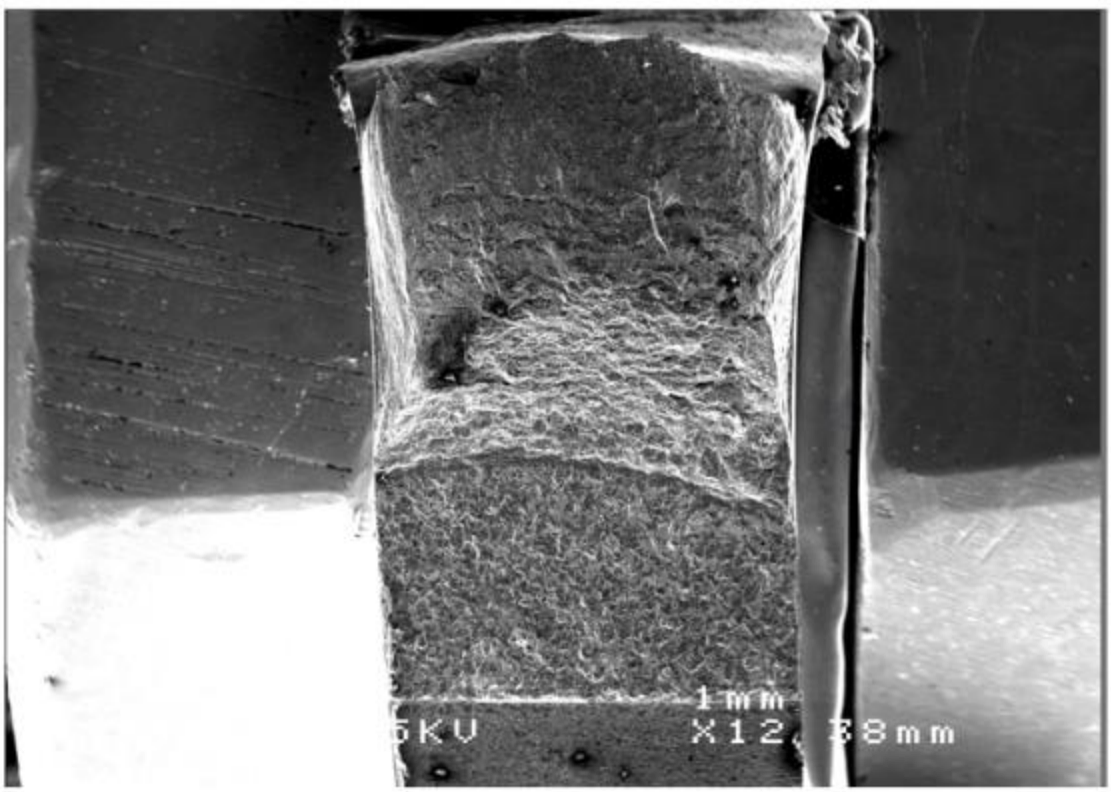
Final fracture does not always happen at single J-value
J_c grows during tearing

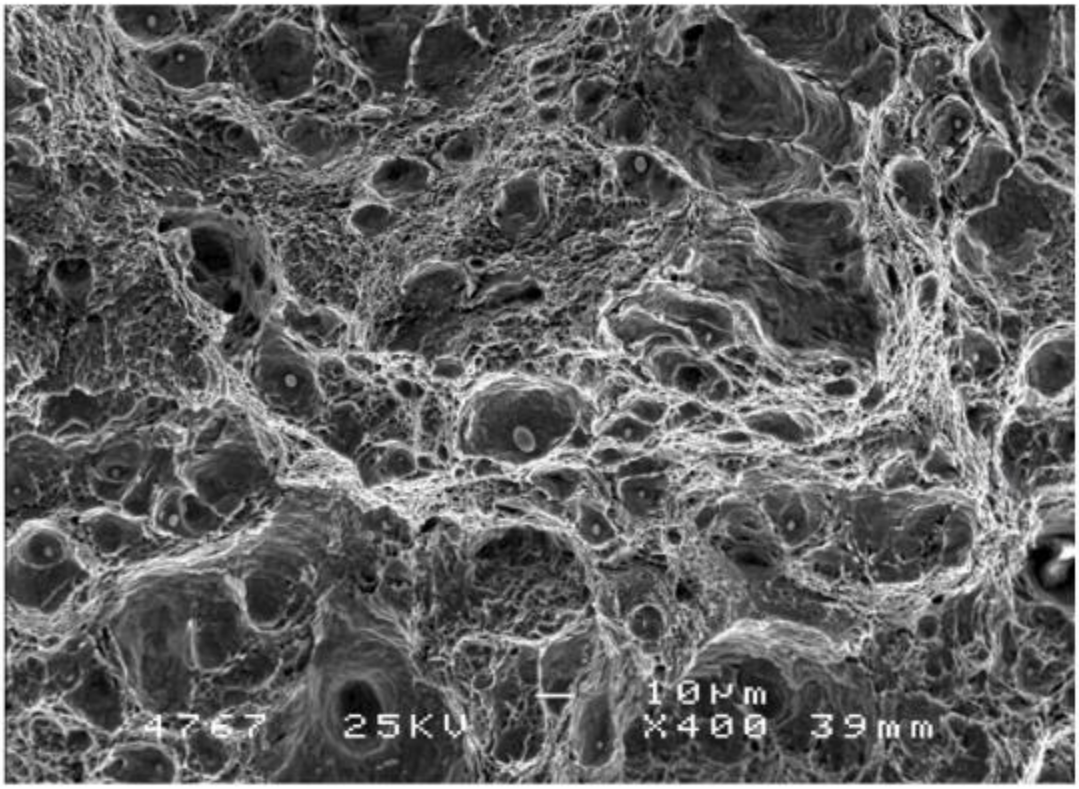


J-R-curves for ductile materials

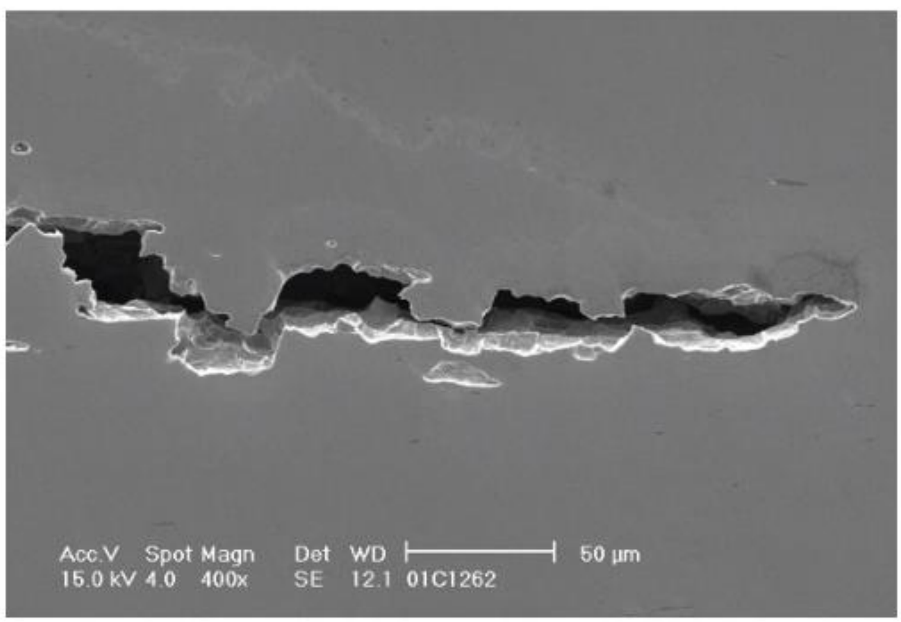


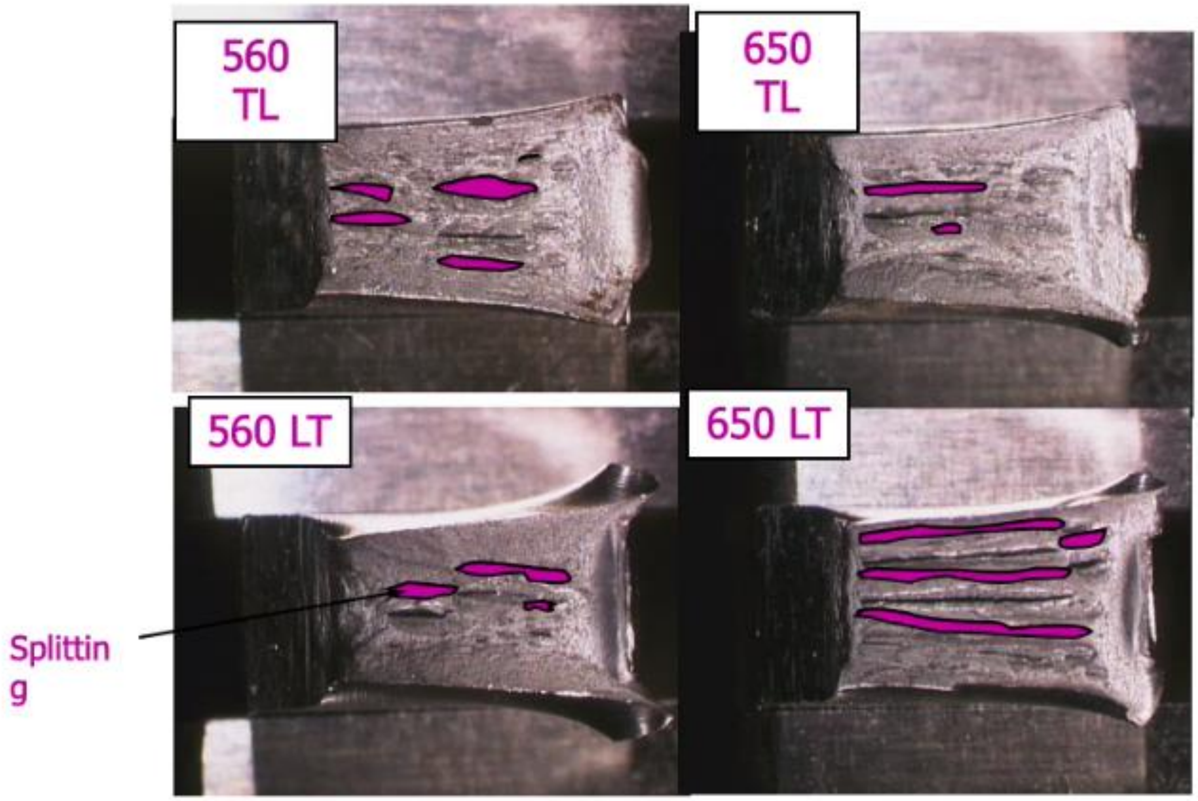

Void Sheets
Dimples


1mm

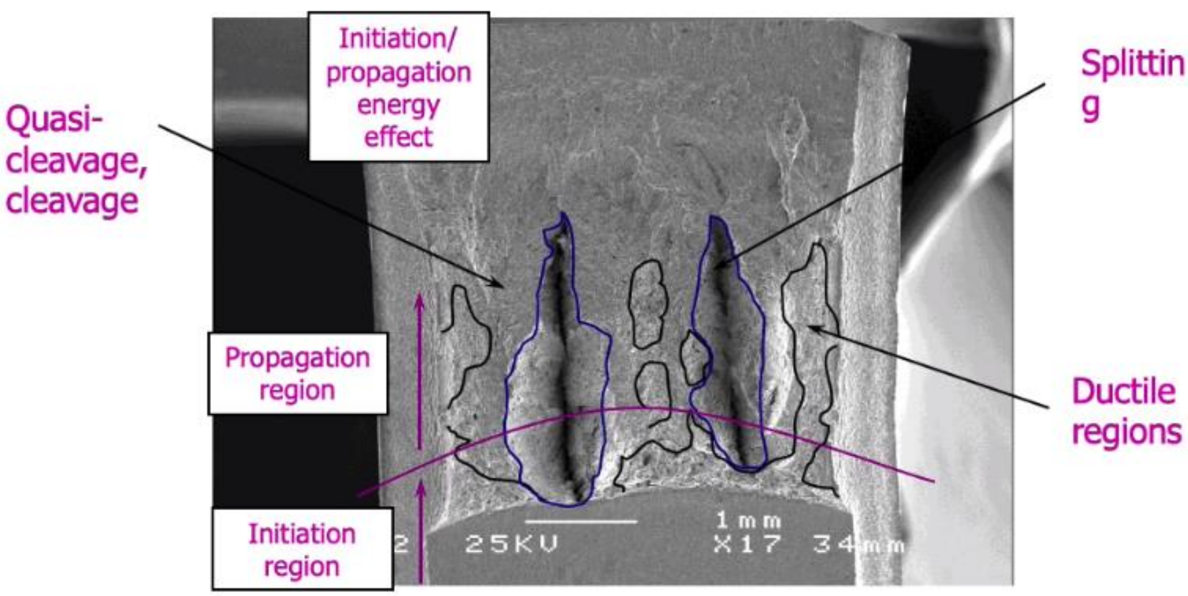


Cross section



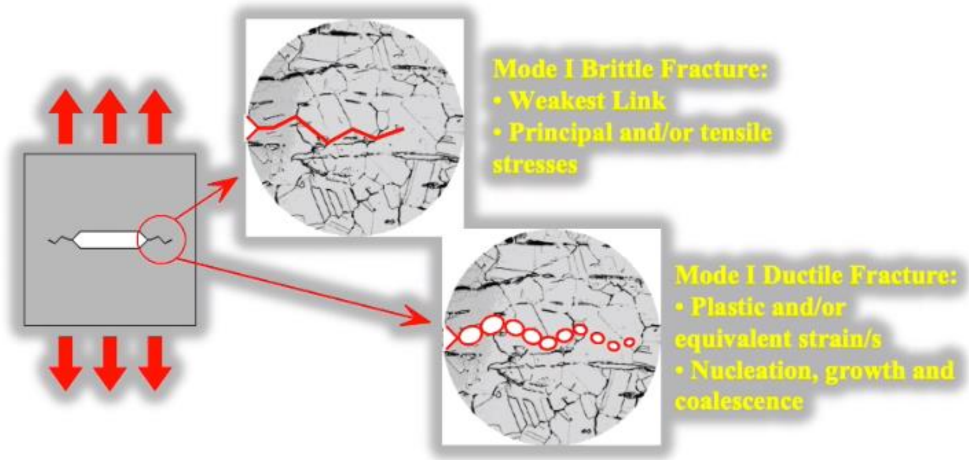


560
TL
650
TL
560 LT
650 LT
Splittin
g

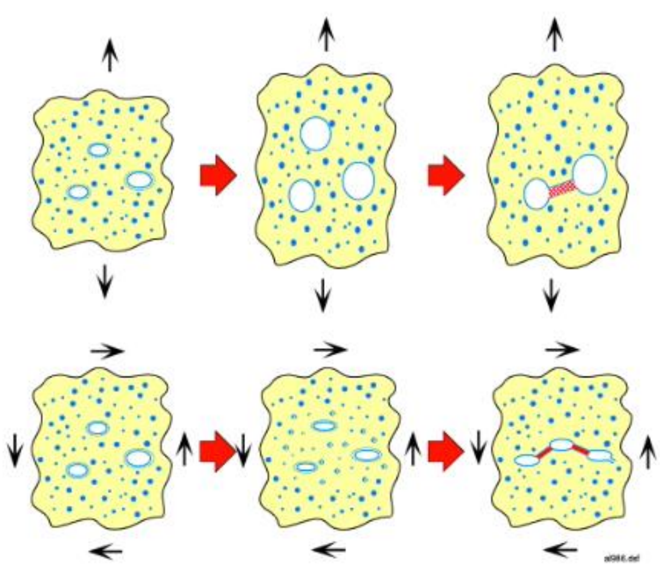


Initiation/
propagation
energy
effect
Splittin
g
Quasi-
cleavage,
cleavage
Propagation
region
Ductile
regions
Initiation
region
1 mm
25KV
X17 34mm

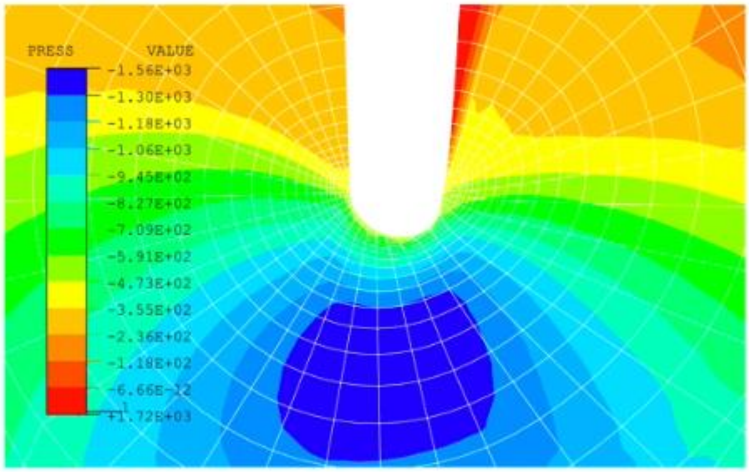
Mekanismi (skemaattisesti)

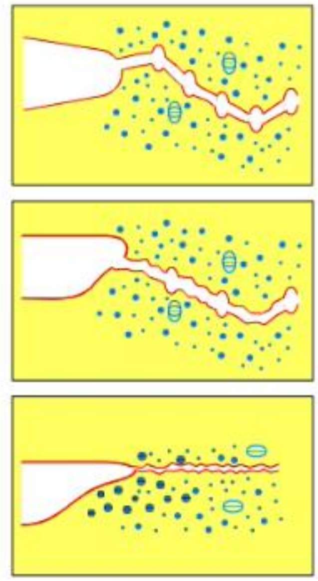


Phases



Blunting





K_{IC} and ductile material

For some materials “ductile fracture” (the mechanism) demands small energy and gives valid K_{Ic} values

K_{Ic} derivation independent of mechanism

Aluminium

Not susceptible to cleavage fracture

Typical failure mode "ductile fracture"

Tearing resistance small

Measured K_{Ic} values small ≈ 25 MPa·m$^{1/2}$

Fracture control in

- **Airplanes**
- **Rockets**

Mechnism vs. Behaviour

Mechnism	Ductile fracture	Brittle fracture
Cleavage fracture		X
Grain boundary fracture		X
Plastic tearing	*X*	*X*