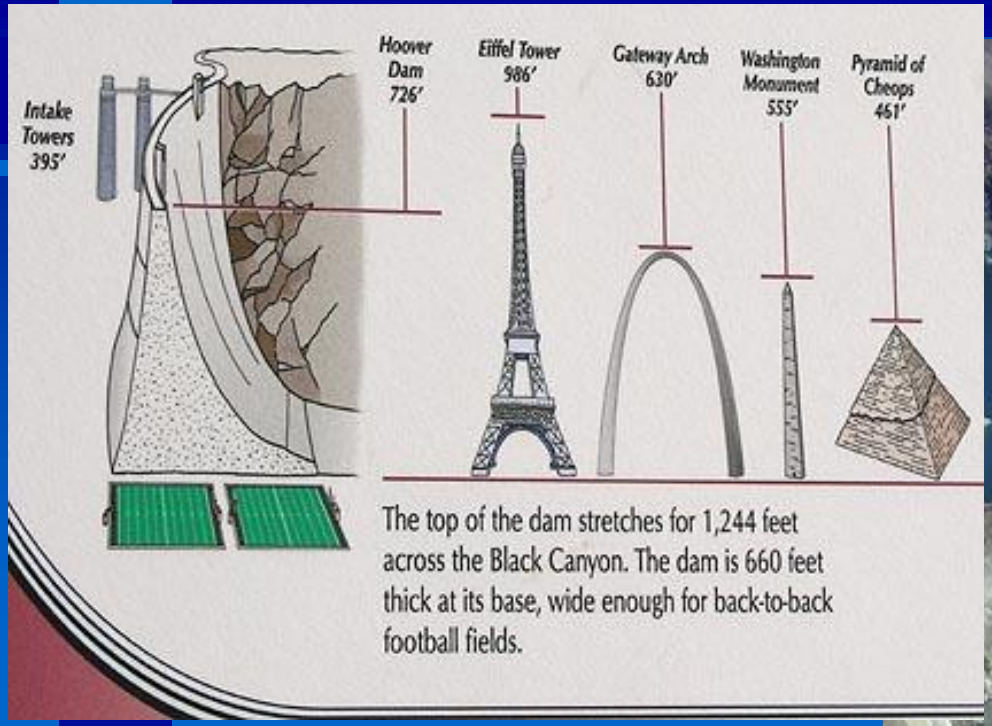
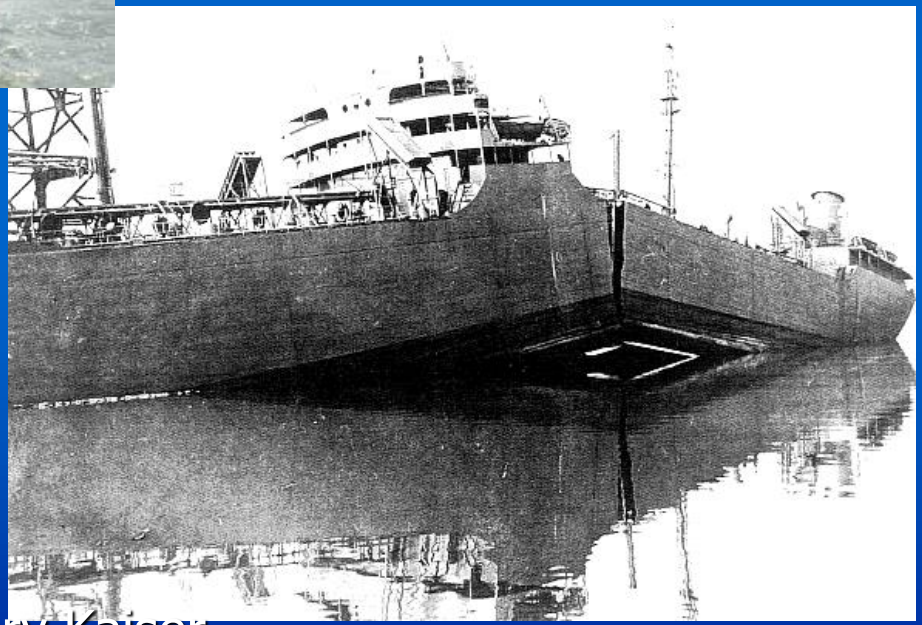


Henry Kaiser, Hoover Dam

Henry Kaiser



Toughness/crack resistance

i. Basic notations (transition fracture behaviour of steels, temperature dependence of strength properties, fractography and failure analysis – basic approach)

ii. (Empirical) tests of toughness/crack resistance (Charpy, Pellini diagram, NDTT)

iii. Linear – elastic fracture mechanics – LEFM (Irwin, fracture toughness tests), Elastic – plastic fracture mechanics EPFM (tests, interpretation)

Resistance of the material against fracture = toughness (ductility)

Fracture is

tough (ductile) — brittle

Metalic materials with fcc lattice temperature is not deciding

- Pure metals – plastic deformation preceding to fracture – fracture is ductile
- Alloys – dislocation blocking – fracture will be brittle

Metallic materials with hcp lattice temperature is deciding for the fracture

- Low number of glide systems – fracture usually brittle
- Only at higher temperatures the plastic deformation is possible.

Metallic materials with bcc lattice
α - iron
temperature, loading rate and stress state are deciding about the type of the fracture

At higher temperatures – fracture usually ductile, at lower temperatures fracture usually brittle

Change of the fracture morphology due to change of the temperature decrease – transition behaviour of steels

Temperature of transition is transition temperature

At accident – fracture surface inspection - FRACTOGRAPHY

Fracture mechanism – type of fracture (physical, not energetic aspects):

Plastic deformation preceding to fracture (void formation and coalescence) – ductile (microvoid) fracture

Fracture without plastic deformation, propagation along grain boundaries and/or along crystalographic planes – cleavage fracture

Resistance of the material against fracture = toughness (ductility)

Fracture is

tough (ductile) — brittle

- Low energy
- Tough

- Brittle

Intergranular

Transcrystalline

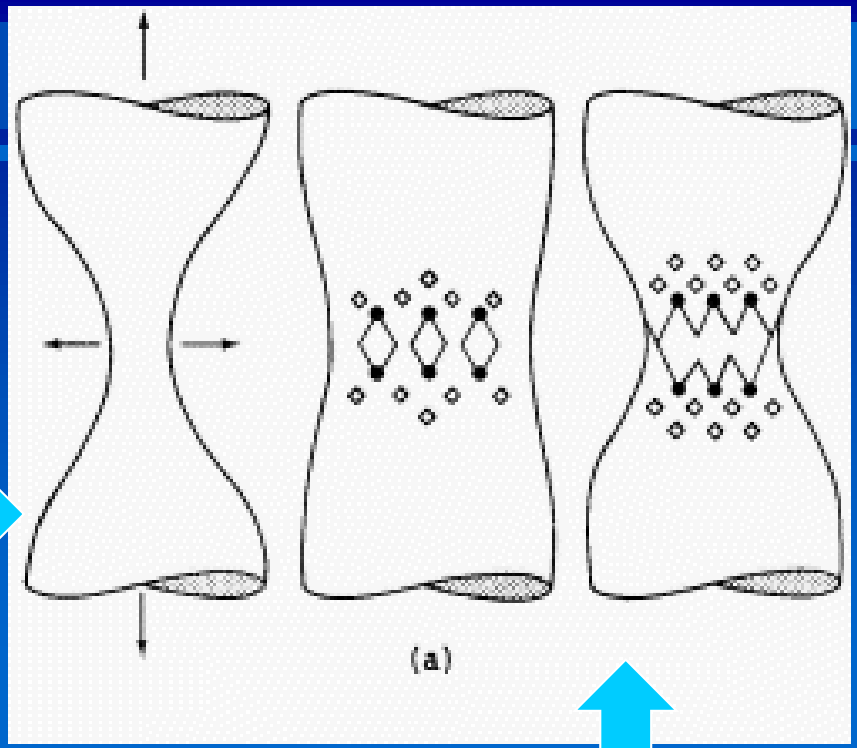
ductile

cleavage

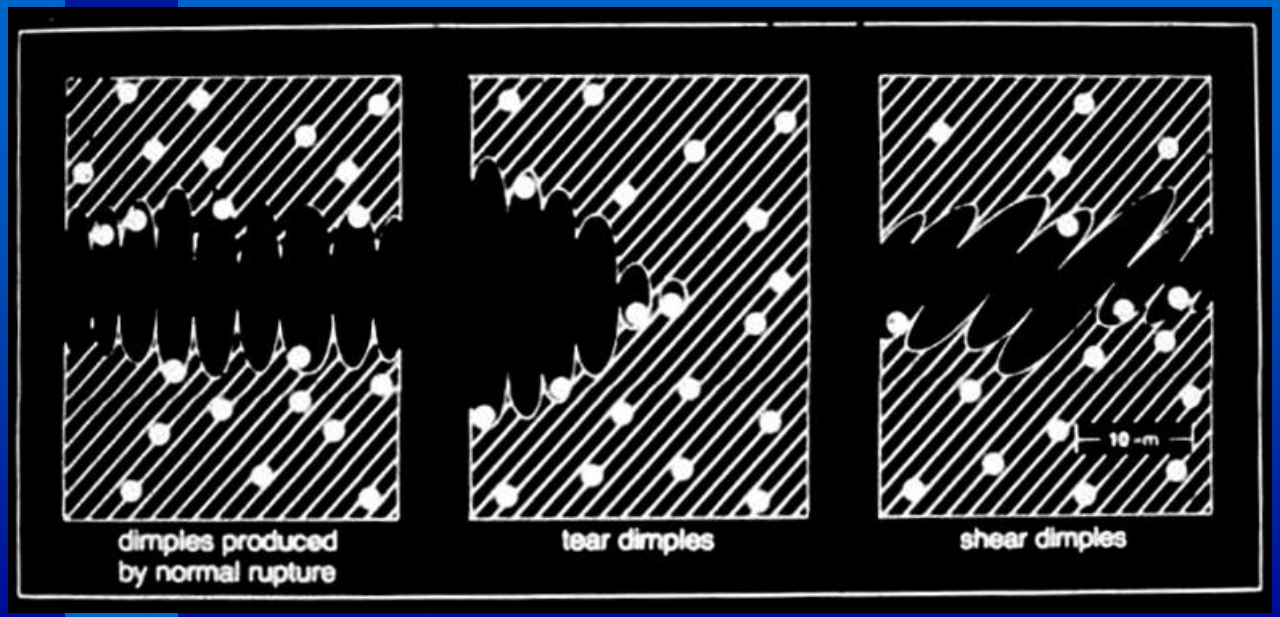
Mechanism point of view

Ductile fracture

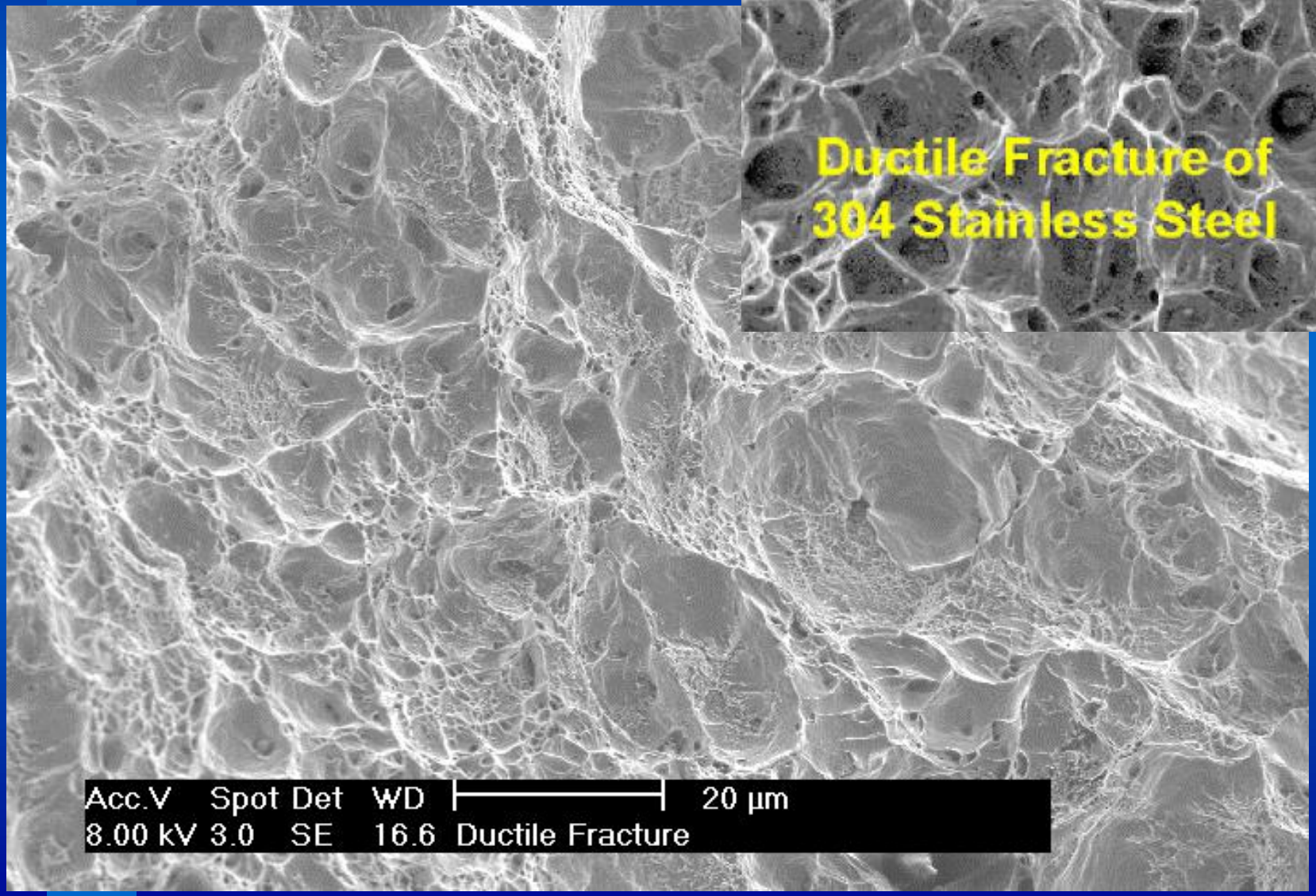
Pure metals

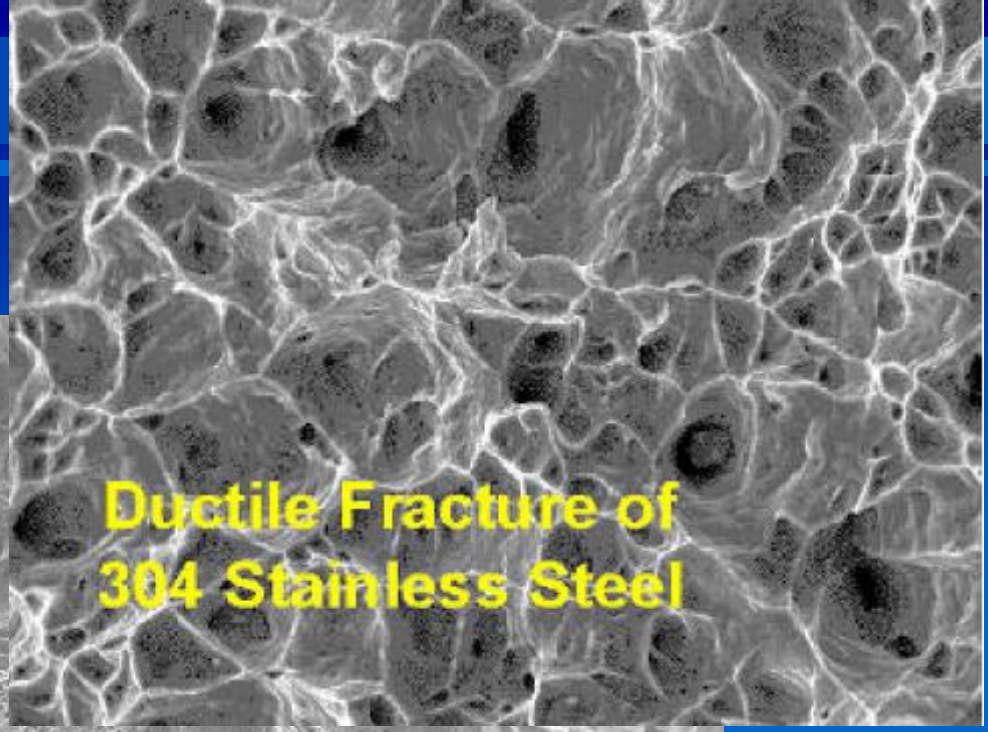


alloys

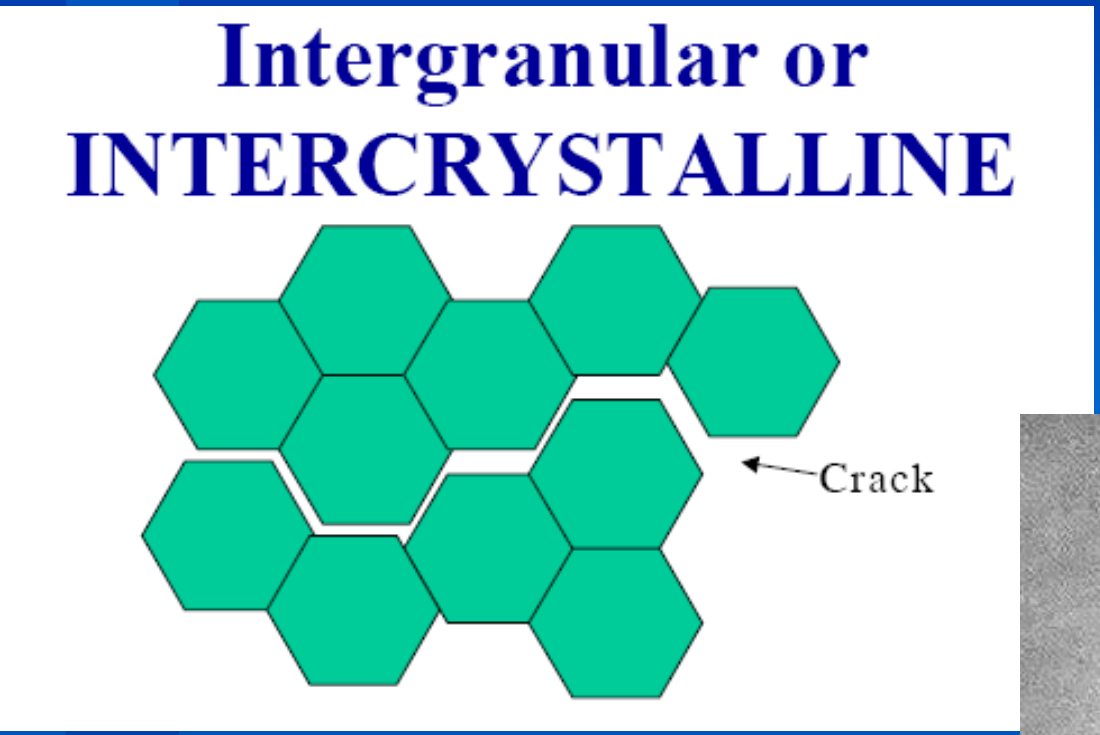


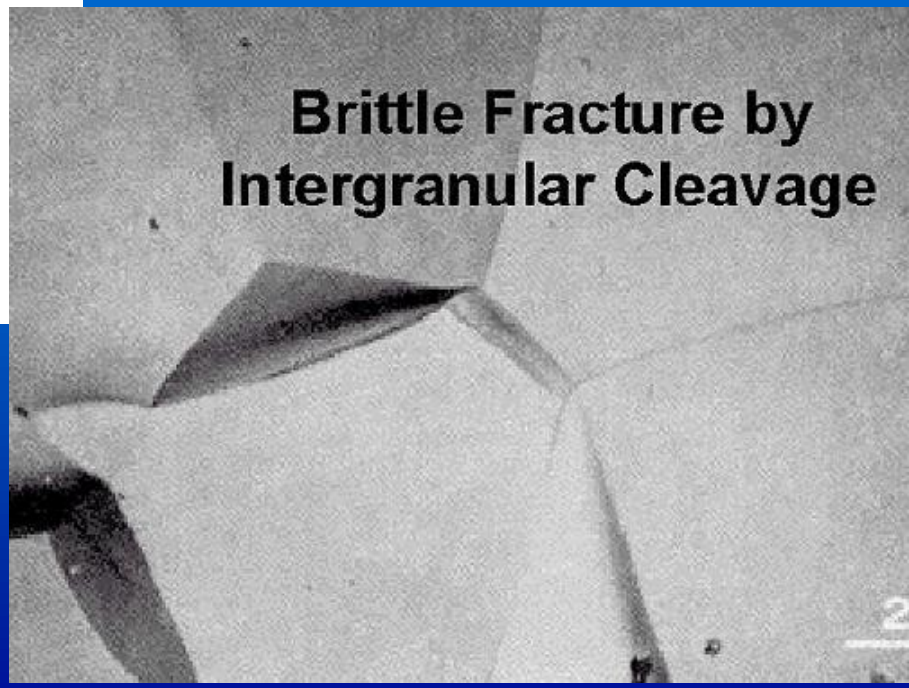
Ductile fracture



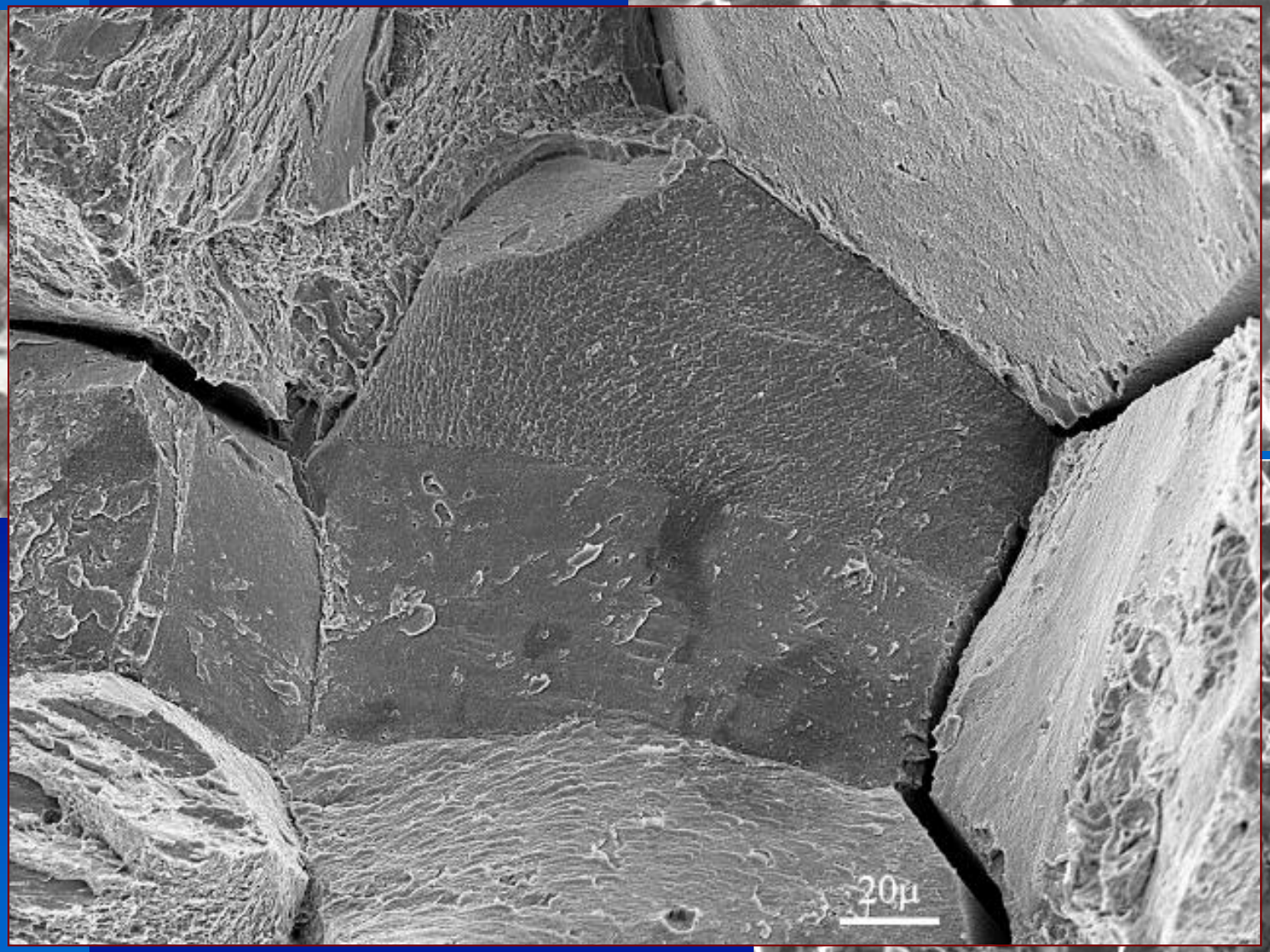


cleavage - intercrystaline

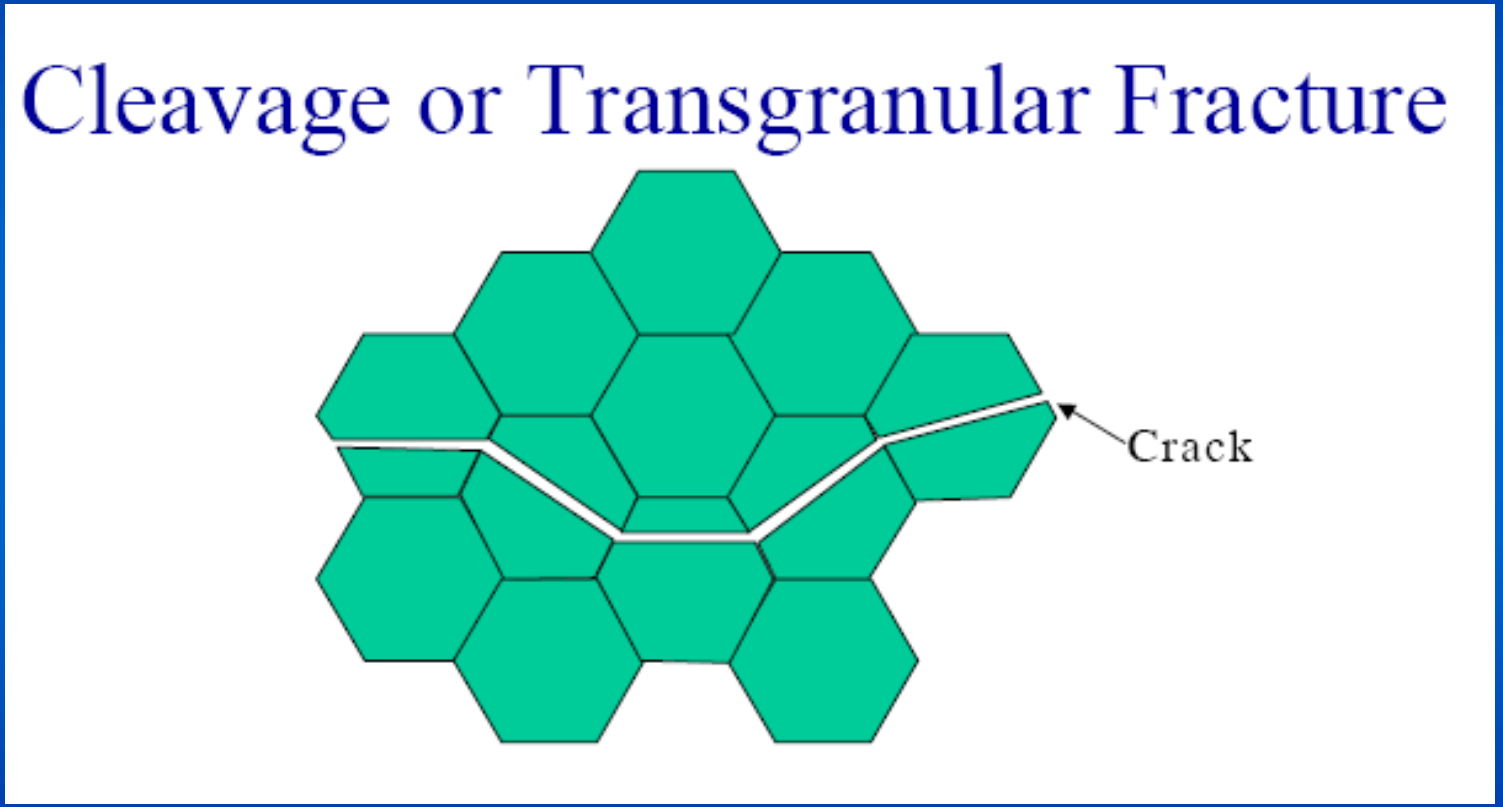




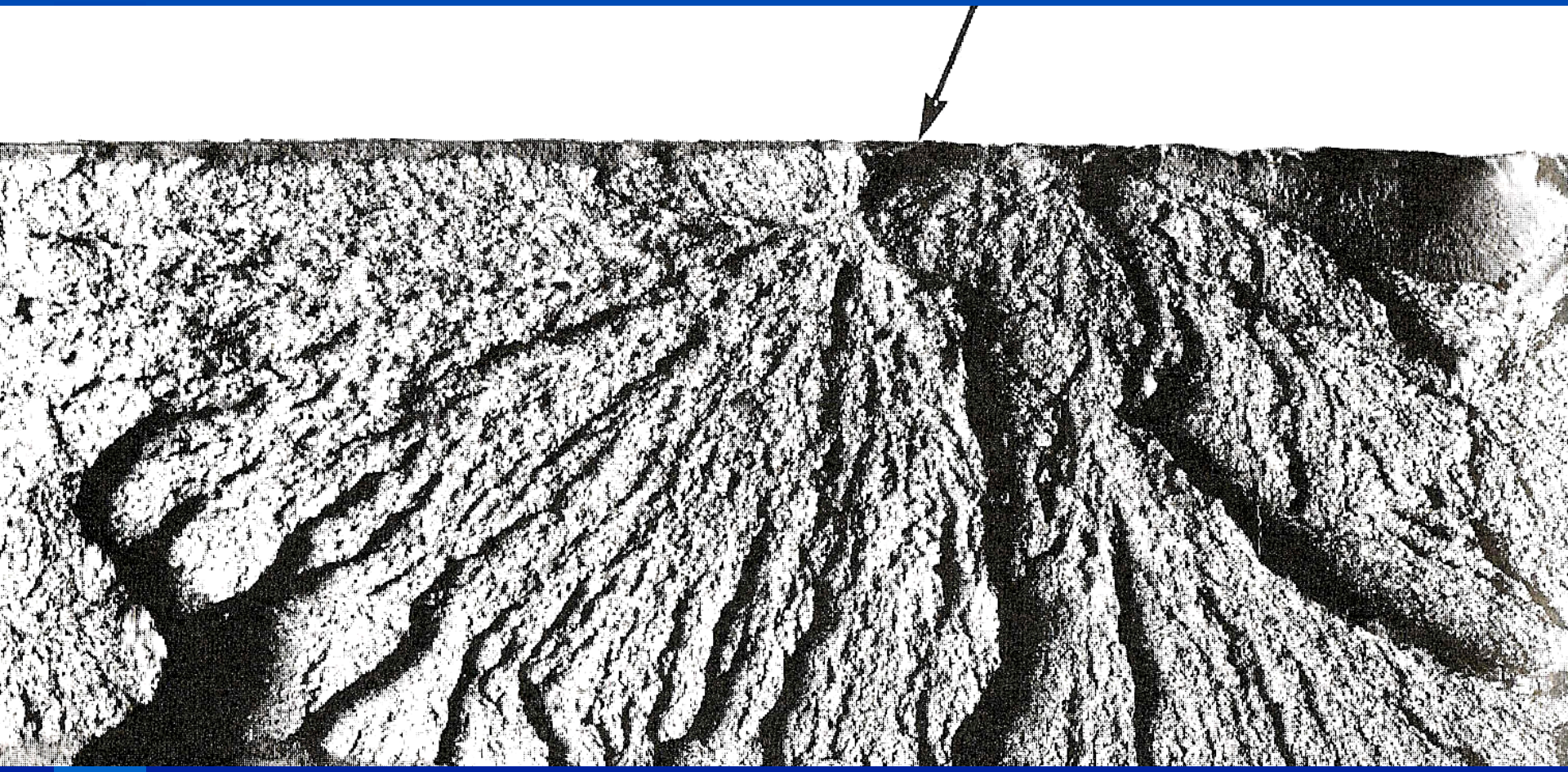
cleavage - intercrystaline

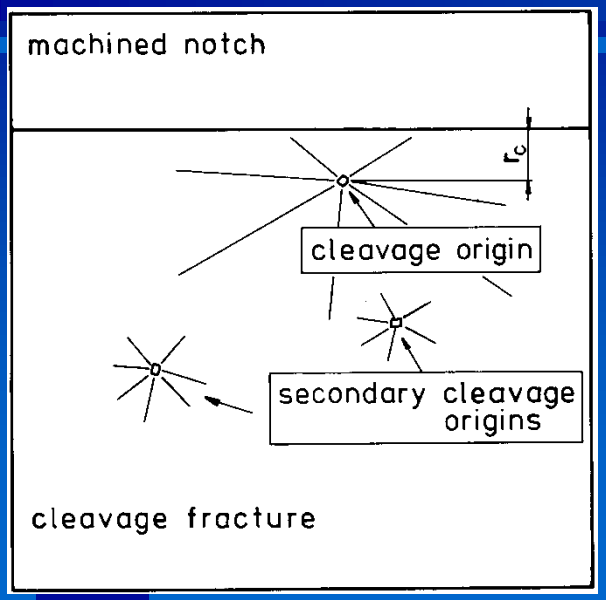


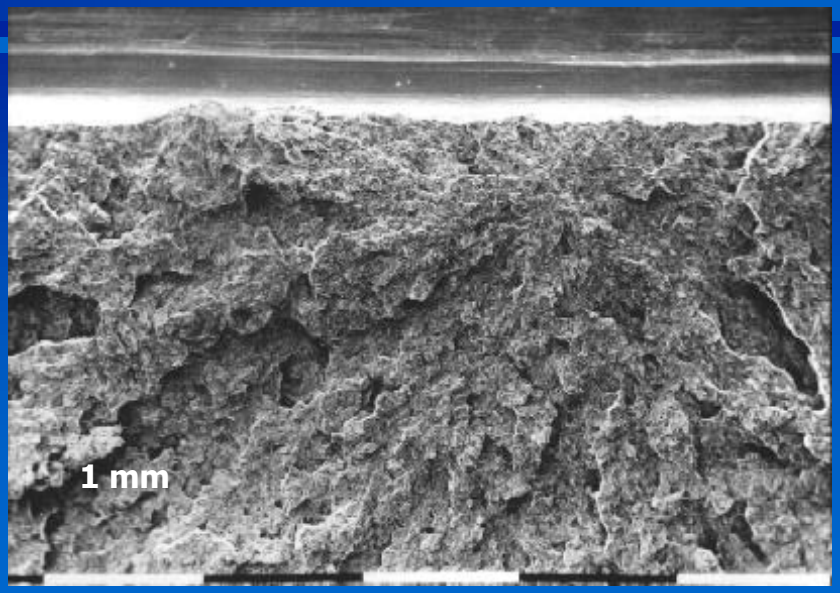
cleavage - transcrystaline

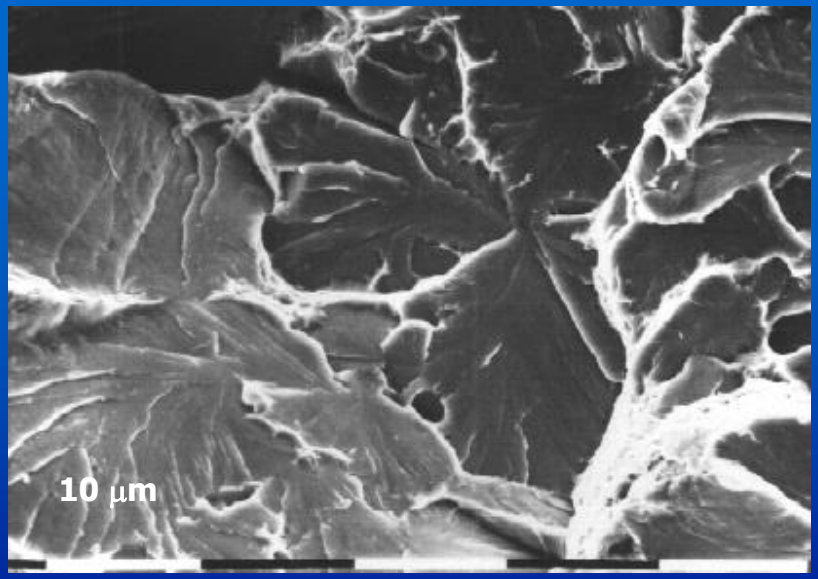


cleavage - transcrystaline

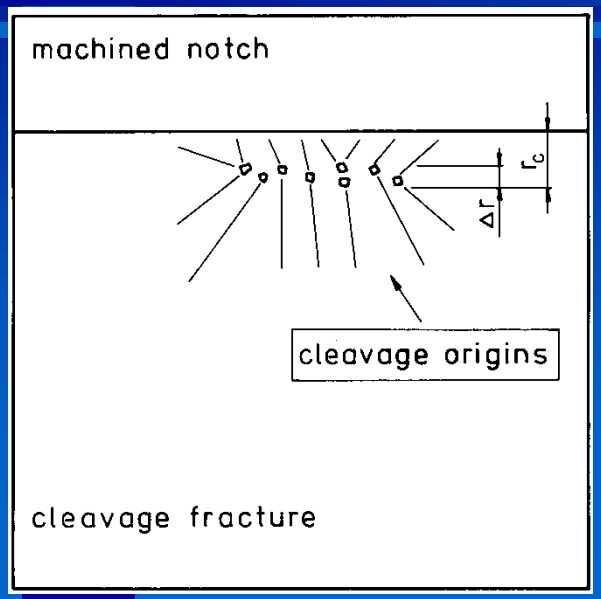


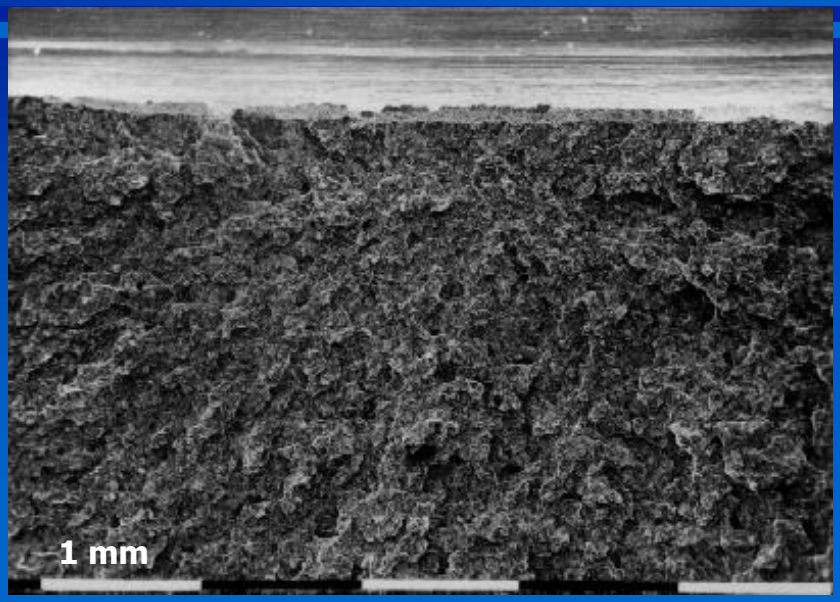


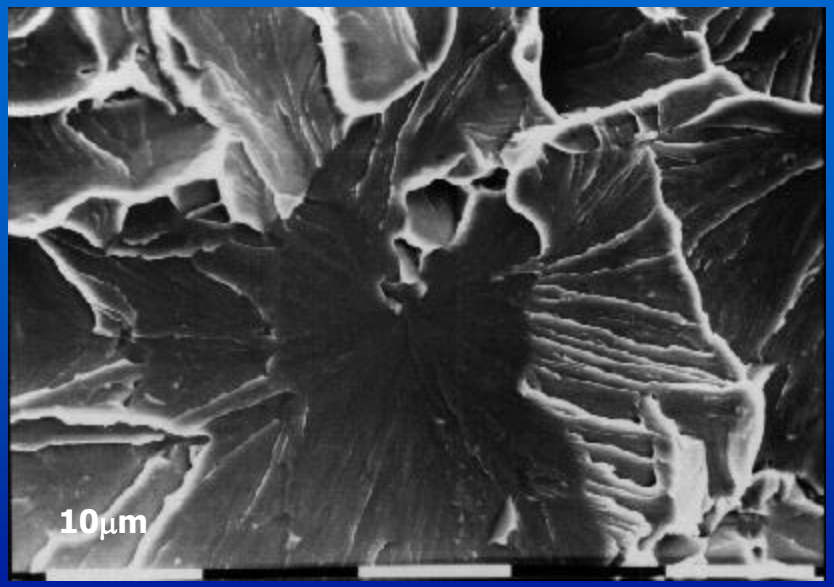




cleavage - transcrystaline

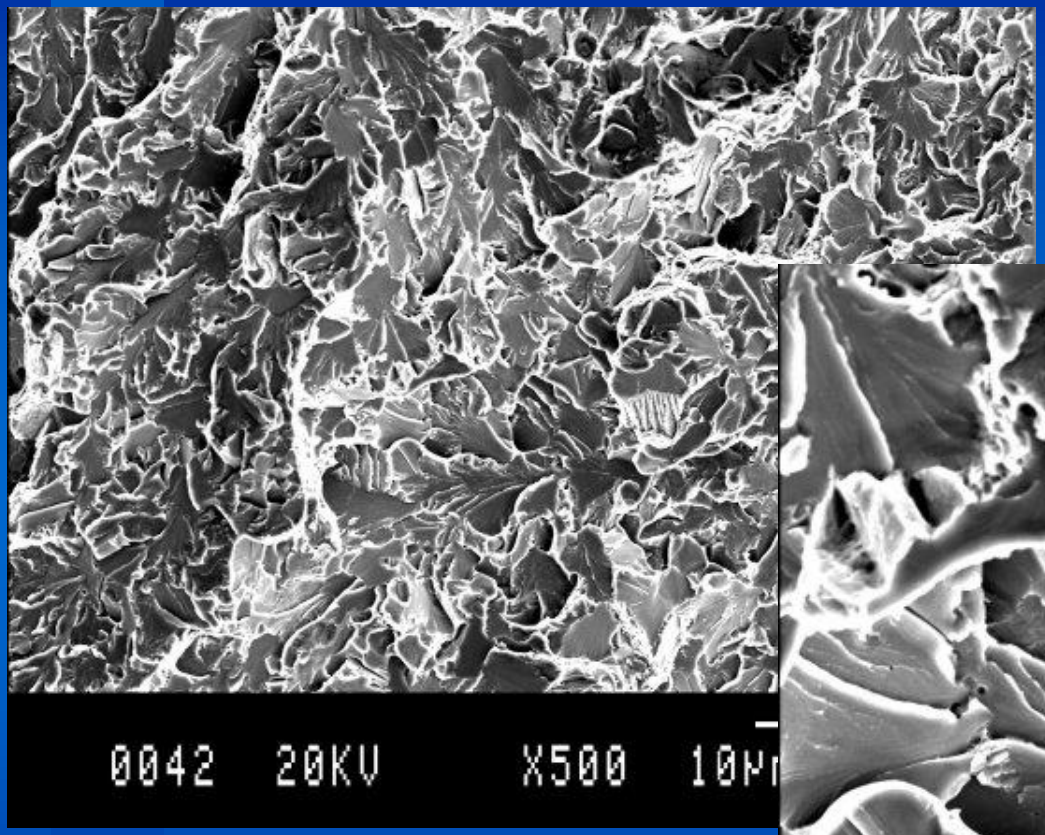


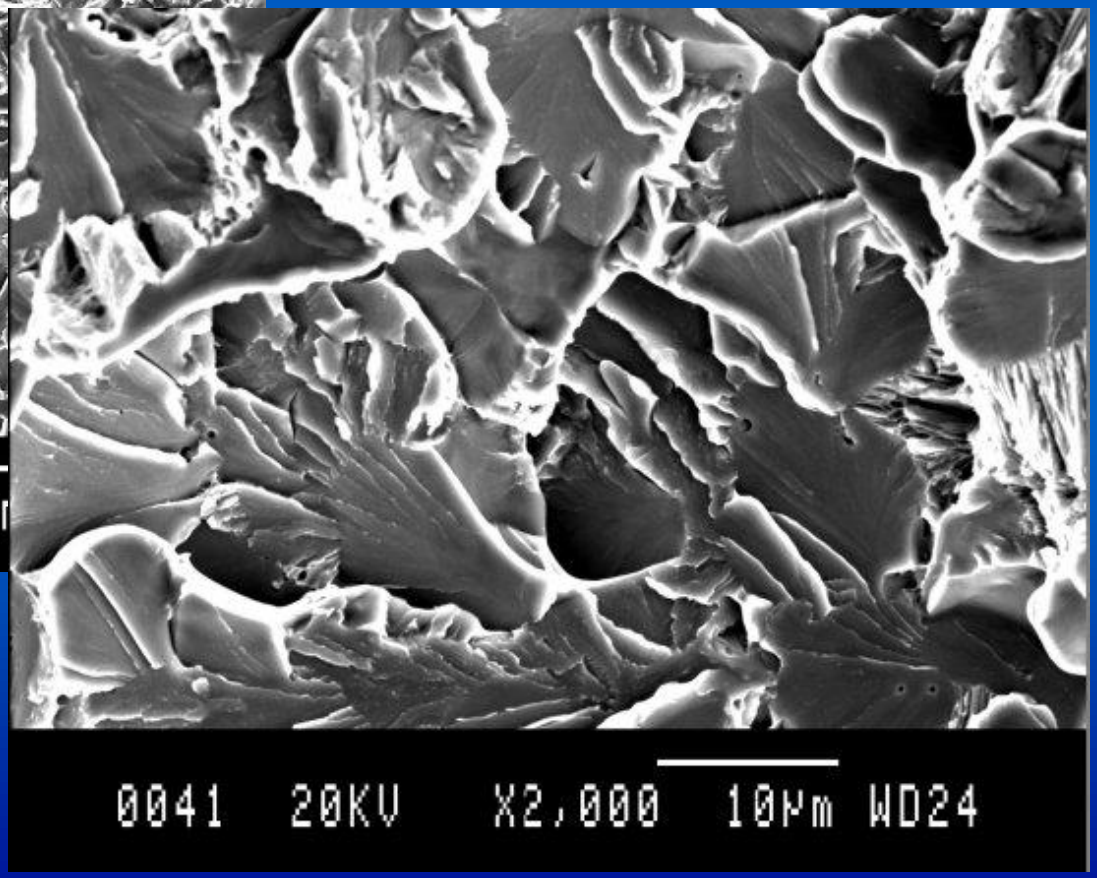




cleavage - transcrystaline

cleavage - transcrystaline



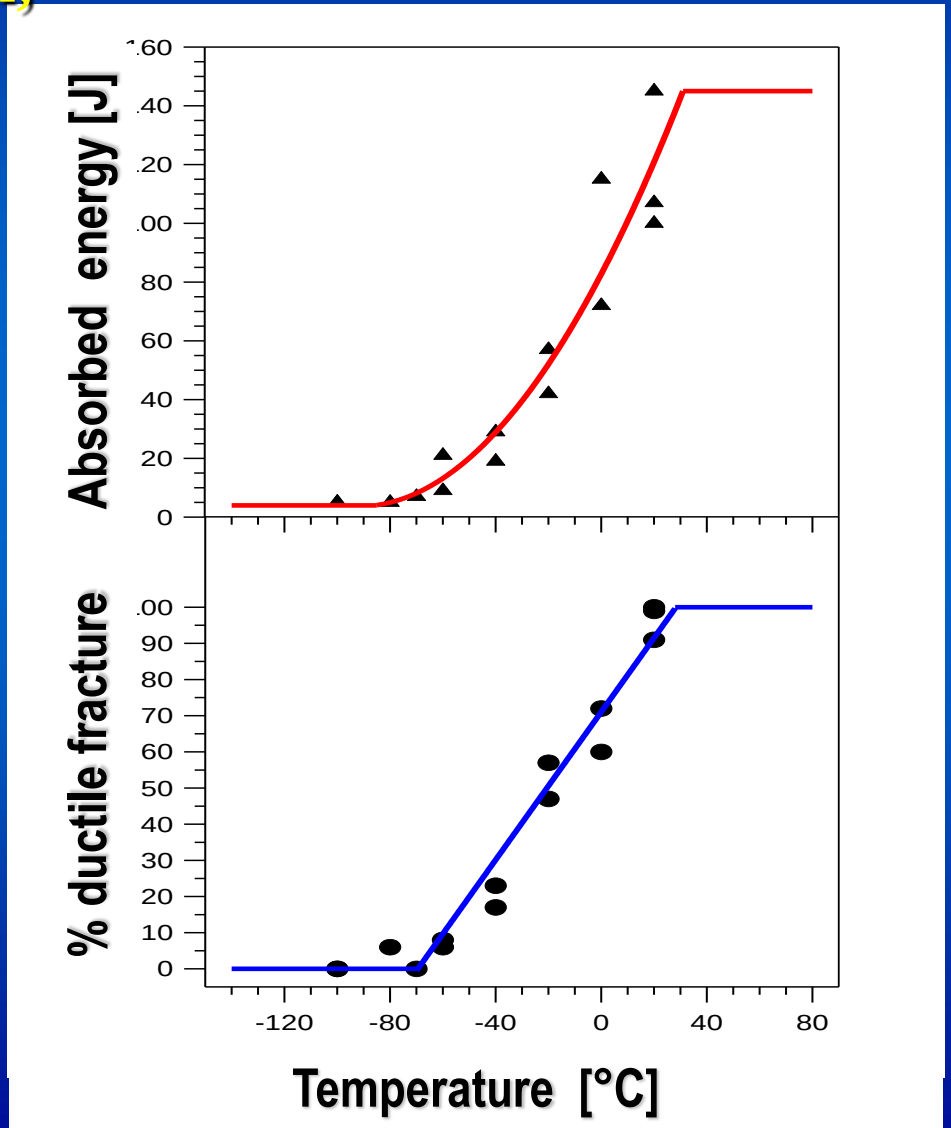


Factors deciding about change of the fracture morphology

- External factors
- Loading conditons: temperature, loading rate, component geometry (stress state, notches presence)

- Internal factors
- Steel microstructure (chemical composition, grain size, effect of other microstructural constiuents)

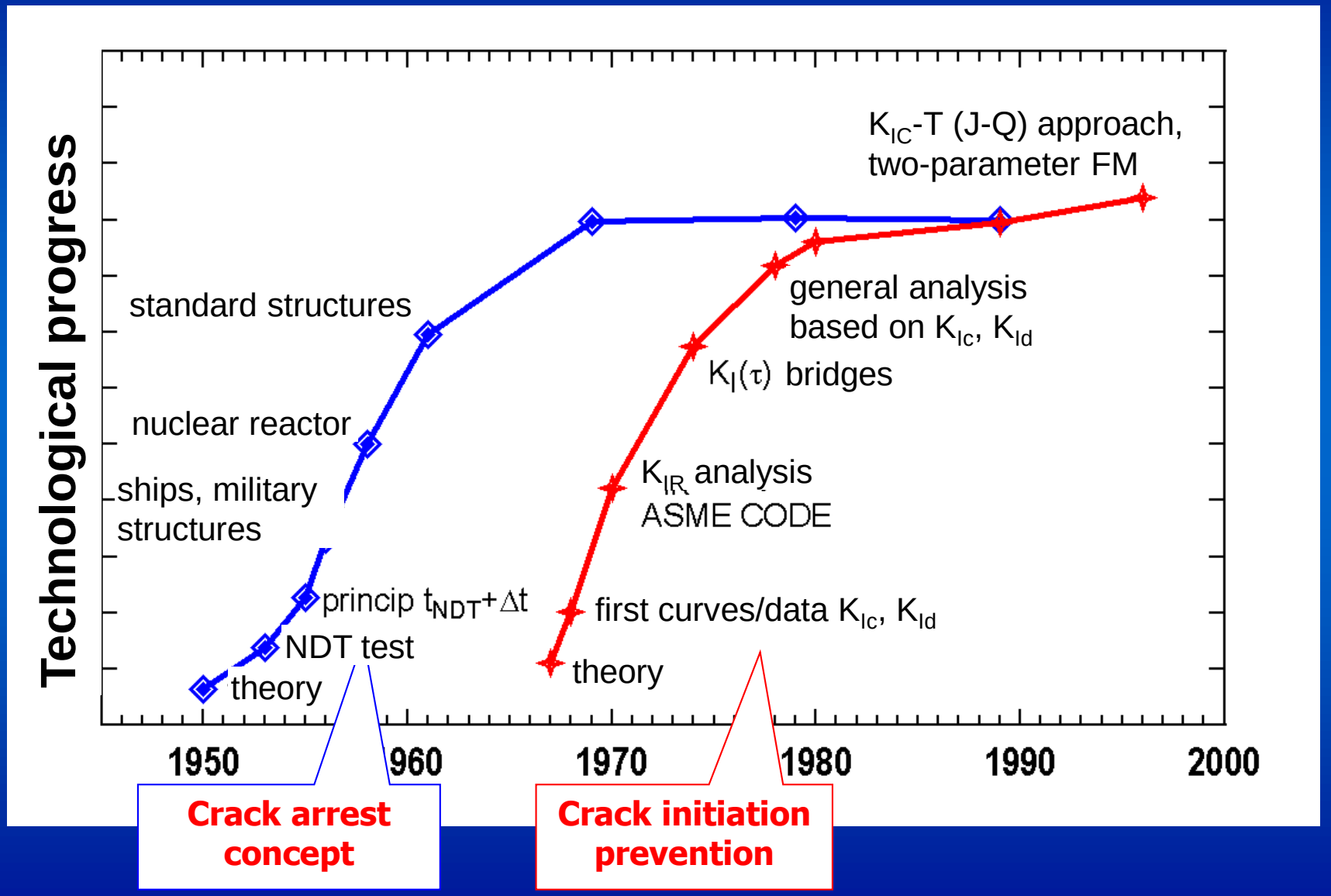
Transition fracture behaviour – change of the fracture morphology, micromechanism, impact energy



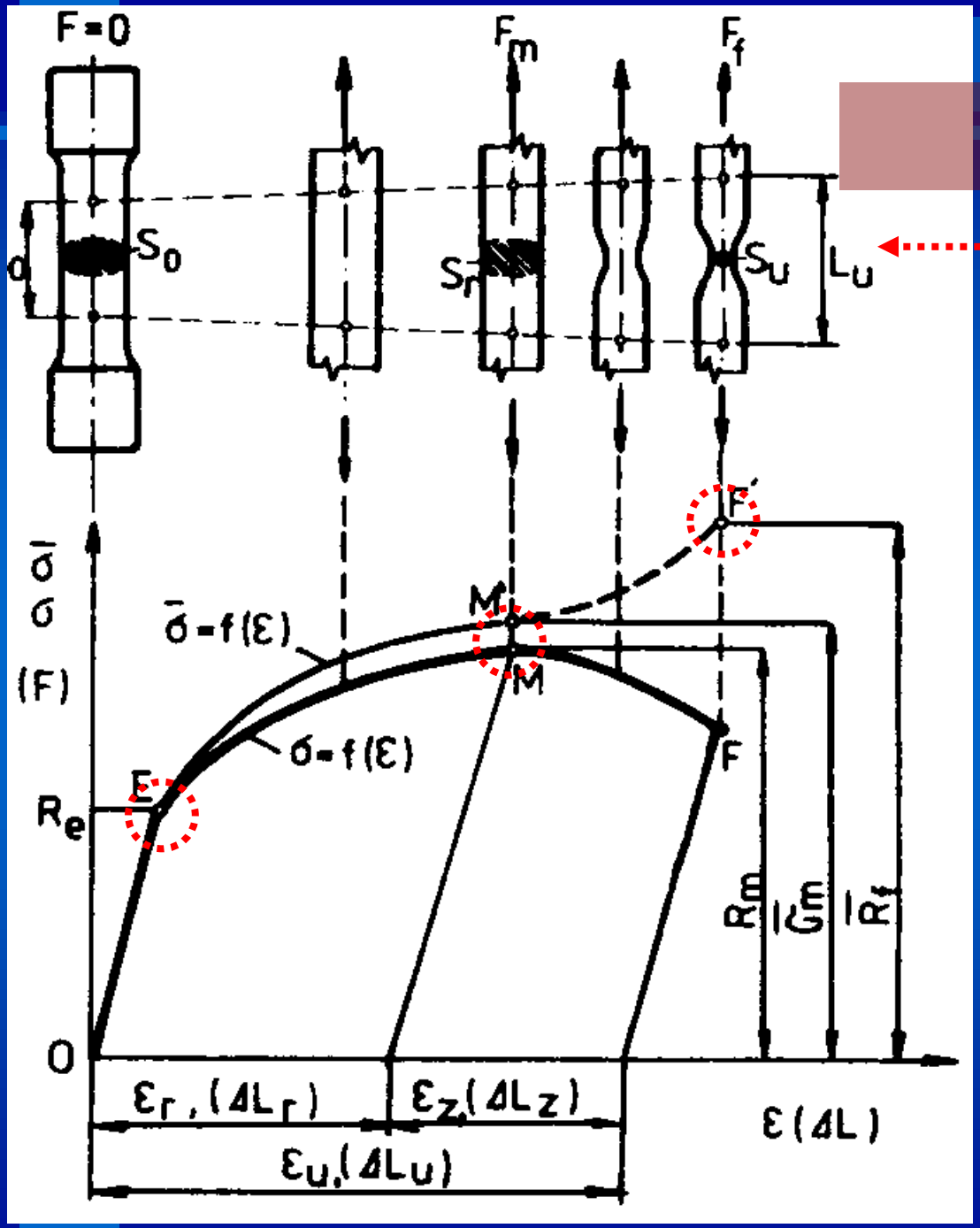
Transition fracture behaviour –
change of the fracture
morphology, micromechanism,
impact energy

How to avoid catastrophic fracture of the component

- crack arrest philosophy - concept of transition temperature
- crack initiation prevention - fracture mechanics concept

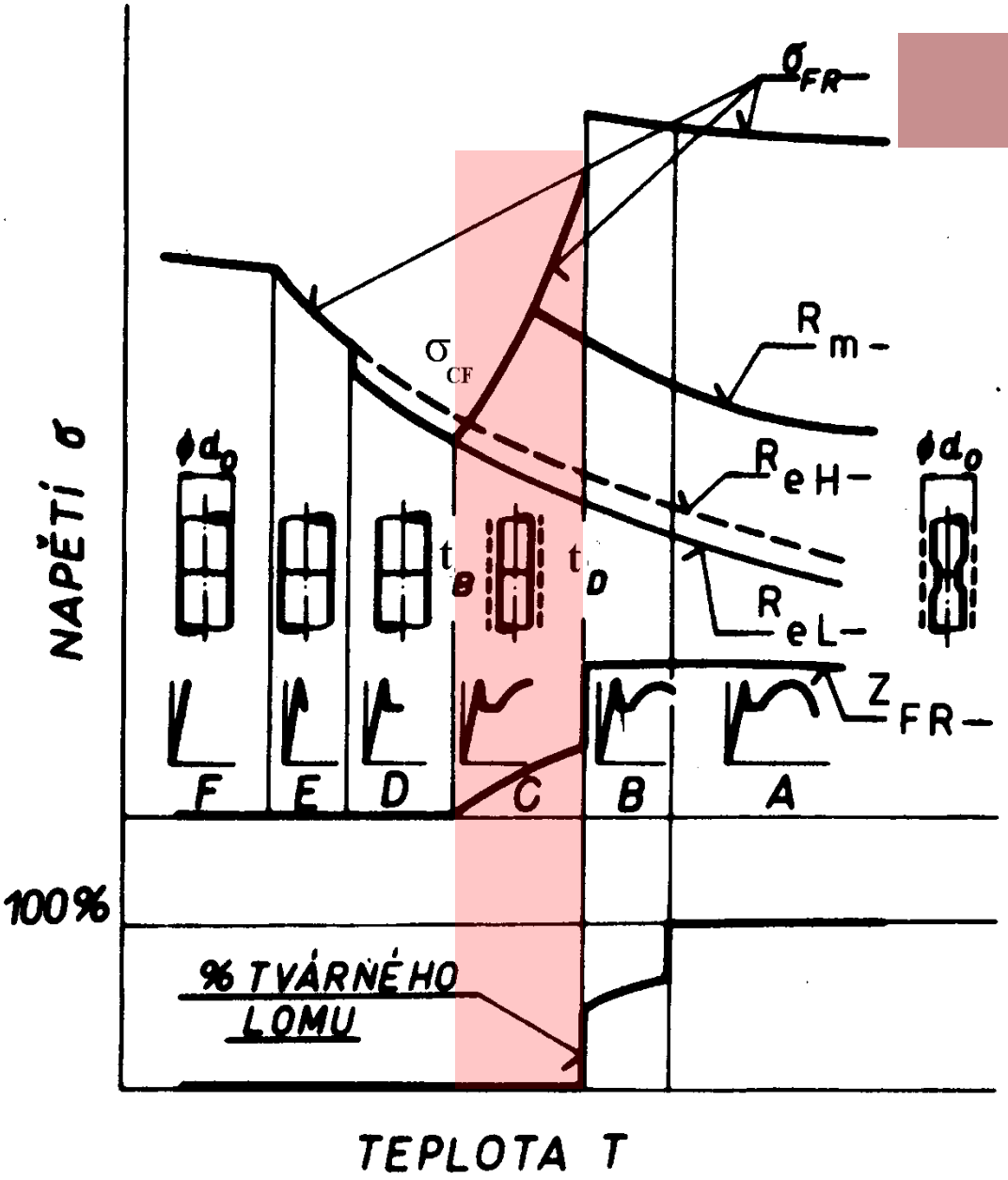

Technological progress
K_{IC}-T (J-Q) approach,
two-parameter FM
standard structures
general analysis
based on K_{Ic}, K_{Id}
$K_I(\tau)$ bridges
nuclear reactor
K_{IR} analysis
ASME CODE
ships, military
structures
princip $t_{NDT}+\Delta t$
first curves/data K_{Ic}, K_{Id}
NDT test
theory
theory
1950
960
1970
1980
1990
2000
Crack arrest concept
Crack initiation prevention

Transition behaviour



- Z
- σ_{fr}
- R_m
- R_e

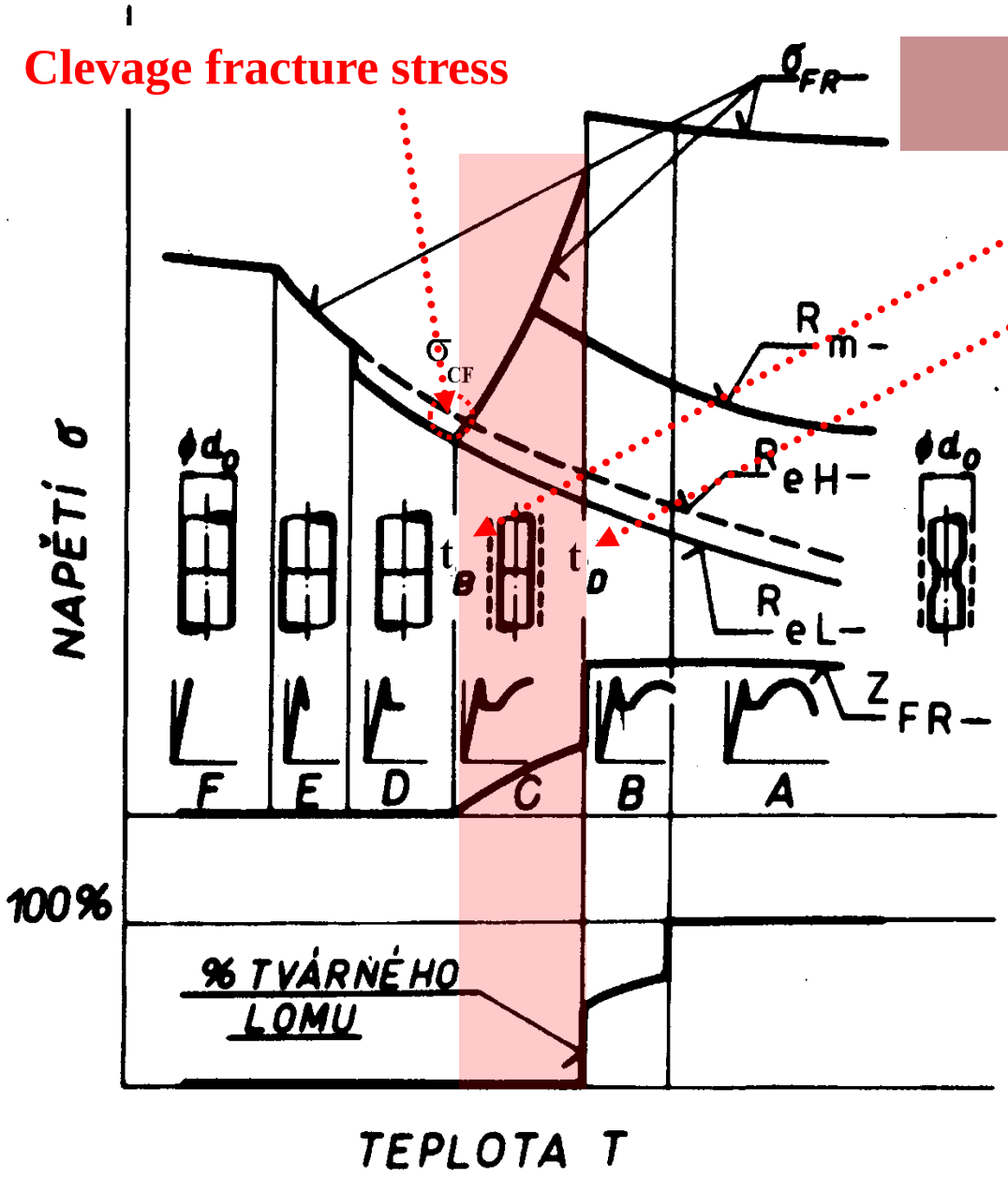
Transition behaviour



low carbon steel

change of tensile diagram in temperature range from 20°C to 269°C

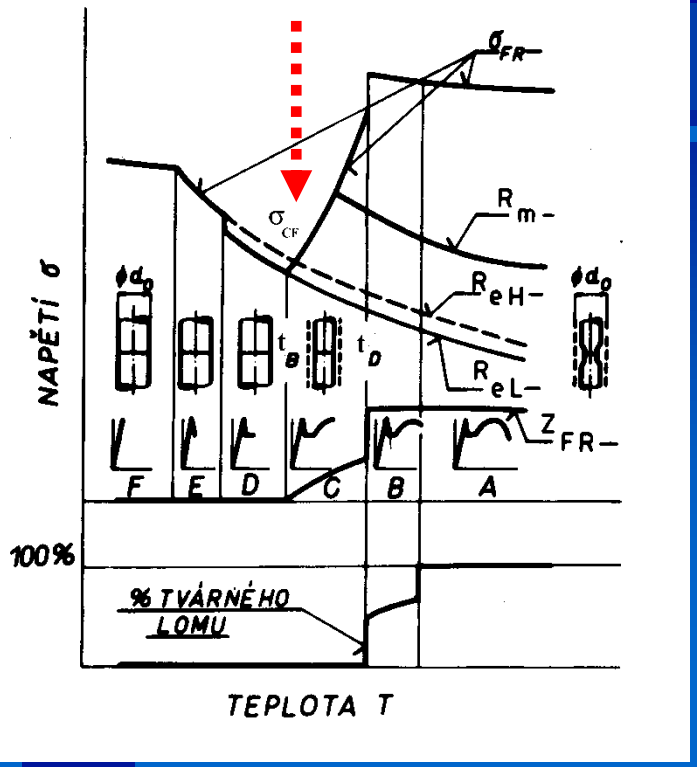
Transition behaviour



t_B – brittlenes transition temp.

t_D – ductility transition temp.

A. Ductile fracture
B. Mixture duct. x cleav.
C. Cleavage fracture
D. Cleavage fracture
E. Cleavage fracture
F. Cleavage fracture



steel	R_e/R_m at +20°C	d (mm)	σ_{CF} (MPa)
11 368	248 /377	0,024	880
11 523	335 / 531	0,019	920
13 030	317 / 482	0,015	1030

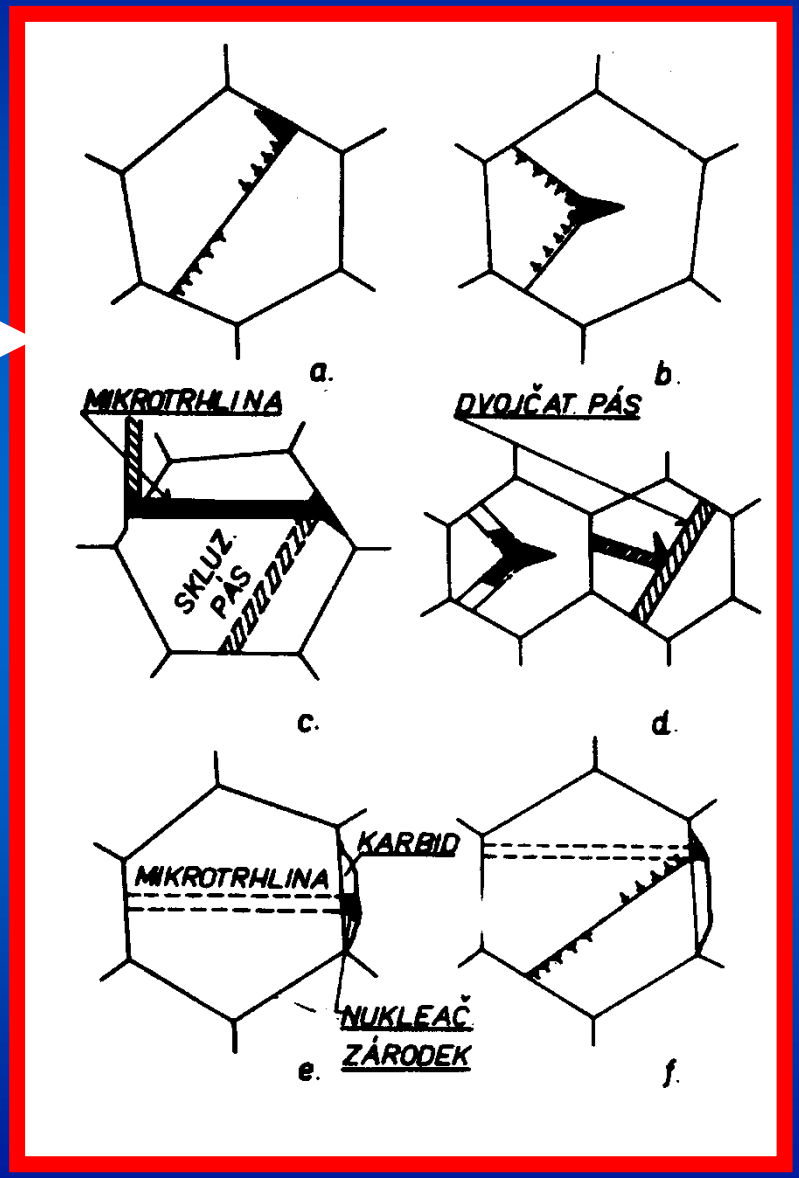
Clevage fracture stress

The lowest stress on the transition curve of tensile fracture stress – at brittleness transition temperature t_B

Material characteristics with physical meaning, do depend on the steel type and microstructure

Clevage fracture stress

Cleavage fracture doesn't occur in under elastic deformations –
in any case plastic deformation precedes to cleavage fracture
- lower/upper yield stress, twinning
- intersection of slip bands, slip band to grain boundary (carbide)



<u>The first condition for cleavage fracture:</u>
plastic deformation - it is the necessary condition but not the sufficient one

$$\sigma_{CF}(g) = R_e = \frac{2G\nu.\gamma_m}{k_y} d^{-1/2}$$

$$\nu = \frac{2\tau_{\max}}{\sigma_1}$$

In order to increase for the cleavage nucleus tensile stress is necessary (it is the cleavage fracture stress)

Second condition for cleavage fracture: and/or cleavage nucleus propagation
critical (cleavage) fracture stress reaching

- cleavage fracture stress is lower than theoretical (cohesive) strength
- value of σ_{CF} depends on steel microstructure
- fracture nucleation and propagation controled

Liberty ships have broken at temperatures close to room temperature (not at liquid nitrogen temp.)

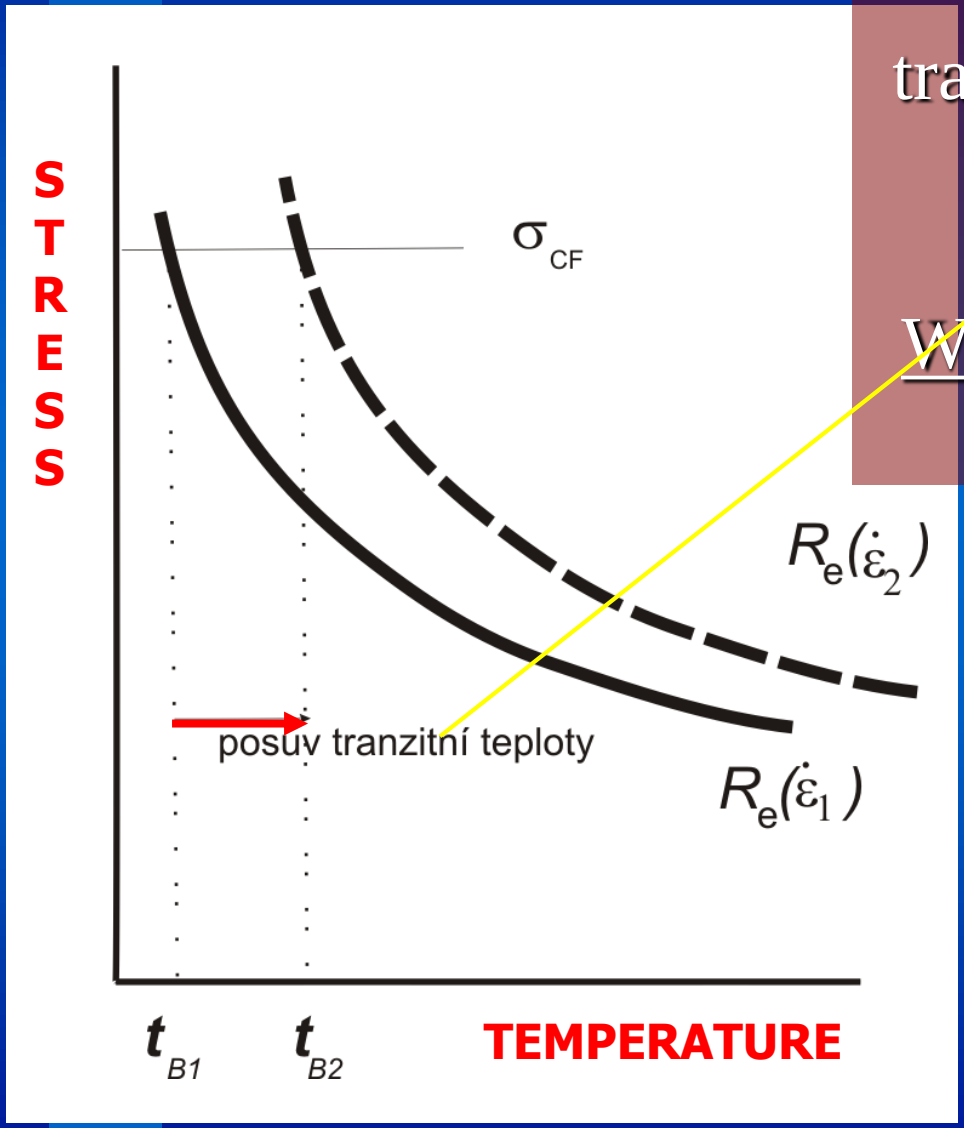
WHY ?

the tensile stress increase on the value of cleavage fracture stress - increased due to

- loading rate increase

- stress concentration effects of notches

Loading rate effect



Higher loading rate moves transition temperatures to higher temperatures !

With increasing loading rate the steel becomes brittler

notches presence → stress field

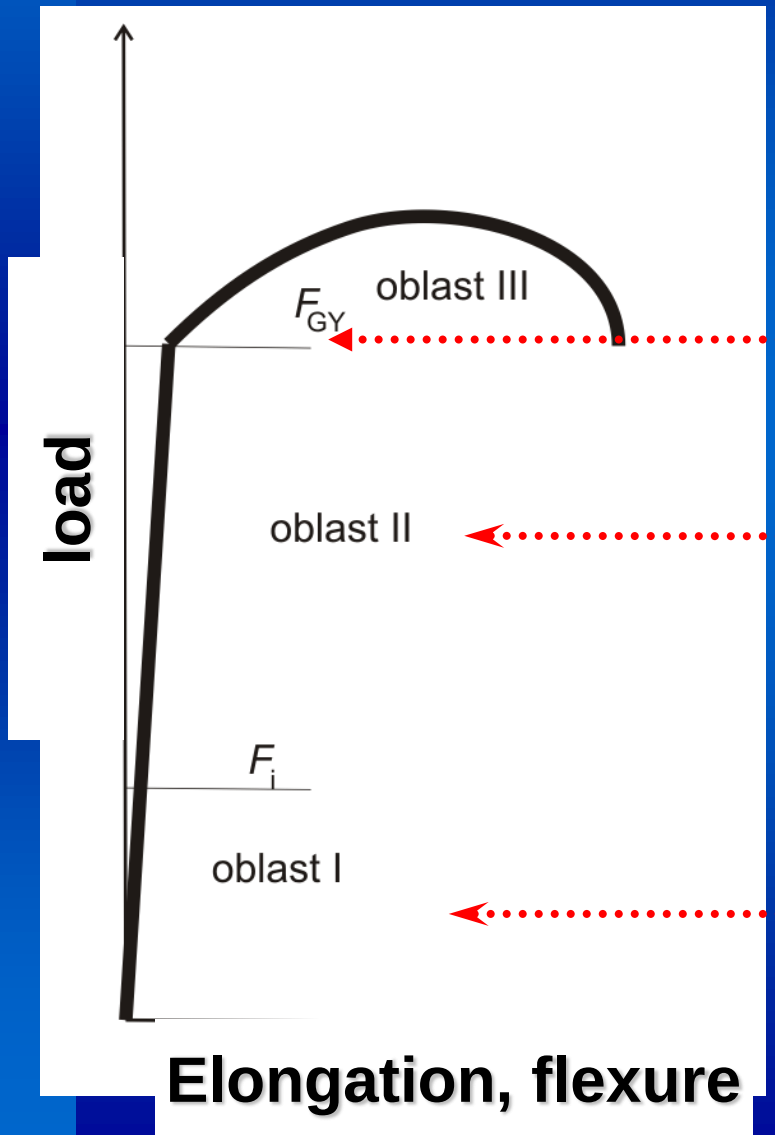
Theoretical stress concentrator $k_t = \alpha$ represents localisation of the stress at notch root at elastic deformation

$$k_t = \frac{(\sigma_{yy})^{max}}{\sigma_n}$$

Plastic stress concentrator represents stress localisation at notch root at local plastic deformation

$$k_{\sigma pl} = \frac{\sigma_{yy}}{R_e}$$

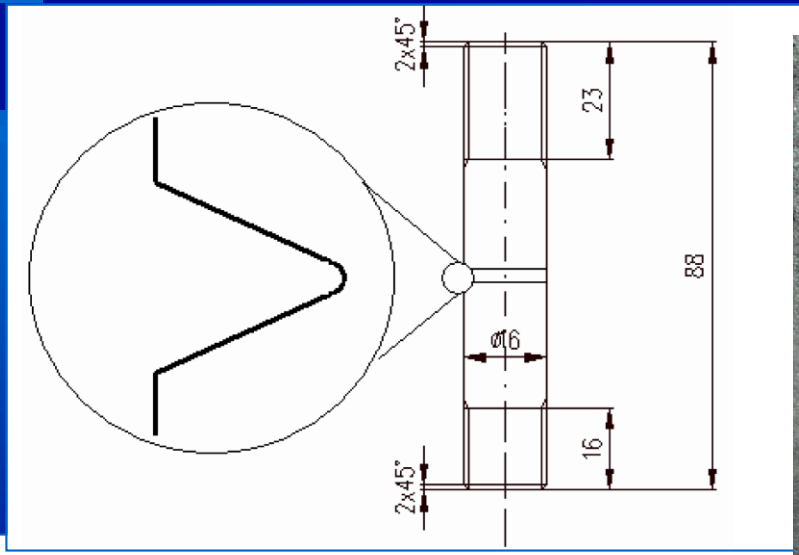
Notched sample loading



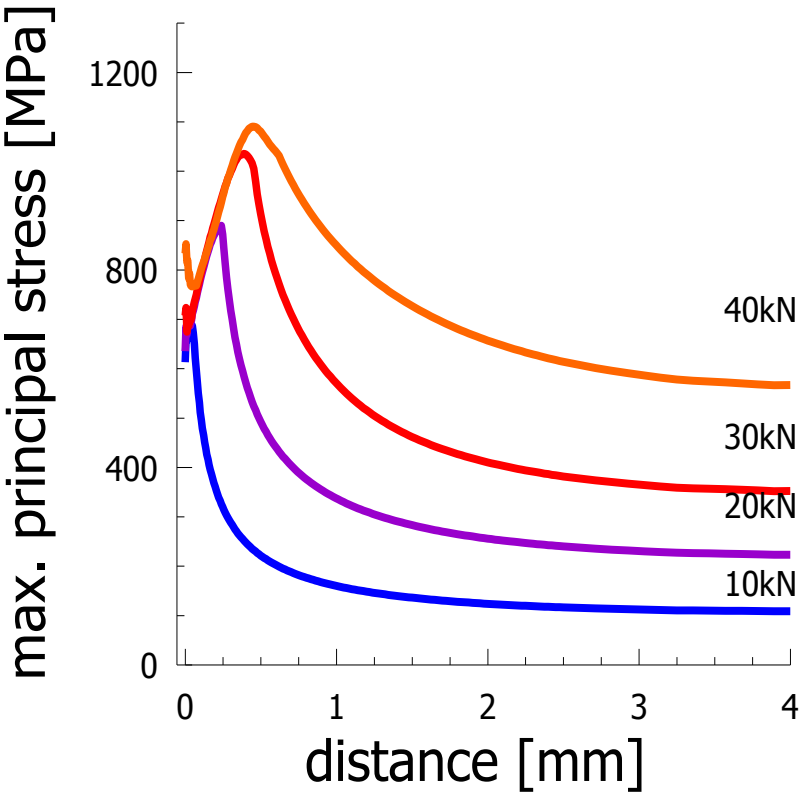
$$k_{\sigma_{pl}}^{max} = \frac{(\sigma_{yy})^{max}}{R_e}$$

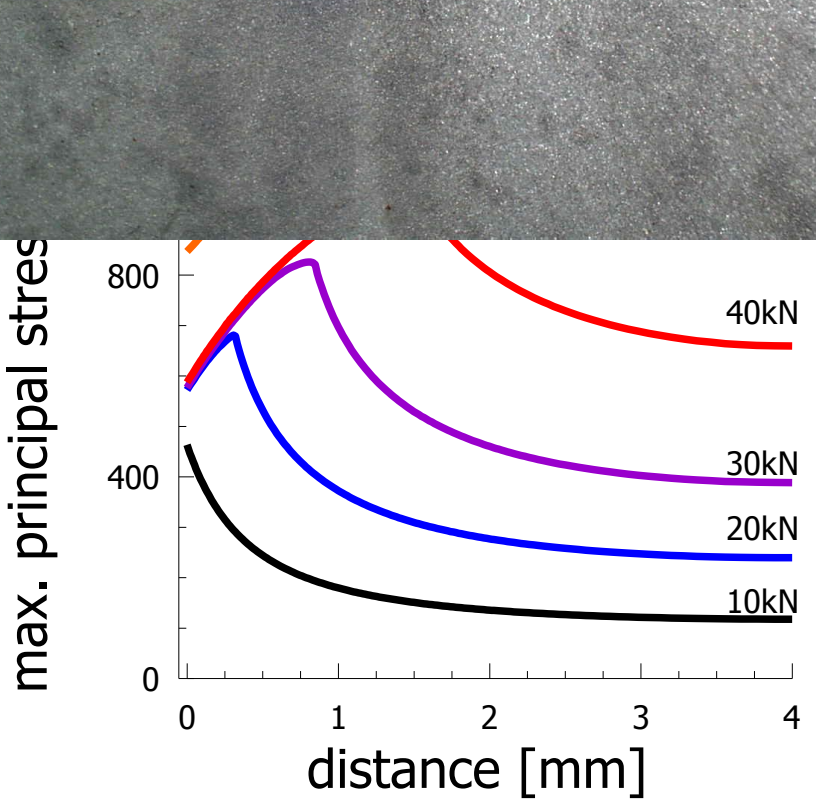
$$k_{\sigma_{pl}} = \frac{\sigma_{yy}}{R_e}$$

$$k_t = \frac{(\sigma_{yy})^{max}}{\sigma_n}$$


2x45°
23
88
ø6
16
2x45°

A
B


max. principal stress [MPa]
1200
800
400
0
0
1
2
3
4
distance [mm]
40kN
30kN
20kN
10kN

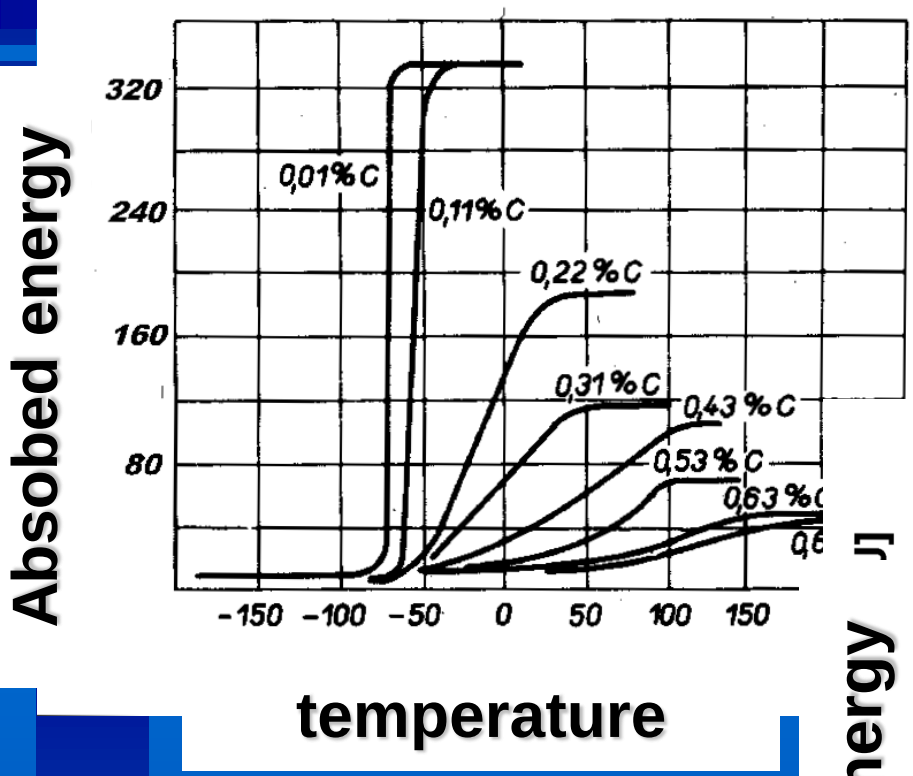

max. principal stres
800
400
0
0
1
2
3
4
distance [mm]
40kN
30kN
20kN
10kN

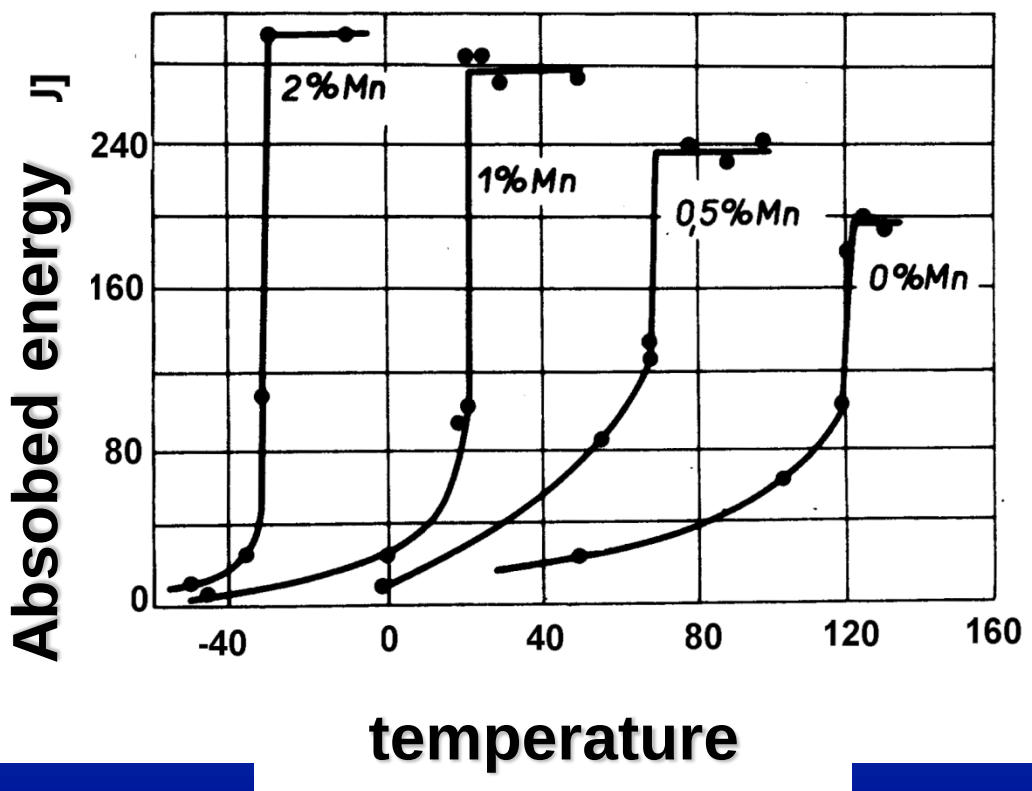
Cleavage fracture stress

cleavage fracture stress controls crack resistance of the steel against brittle fracture not only at uniaxial loading but also in triaxial stress state (samples/components with notches)

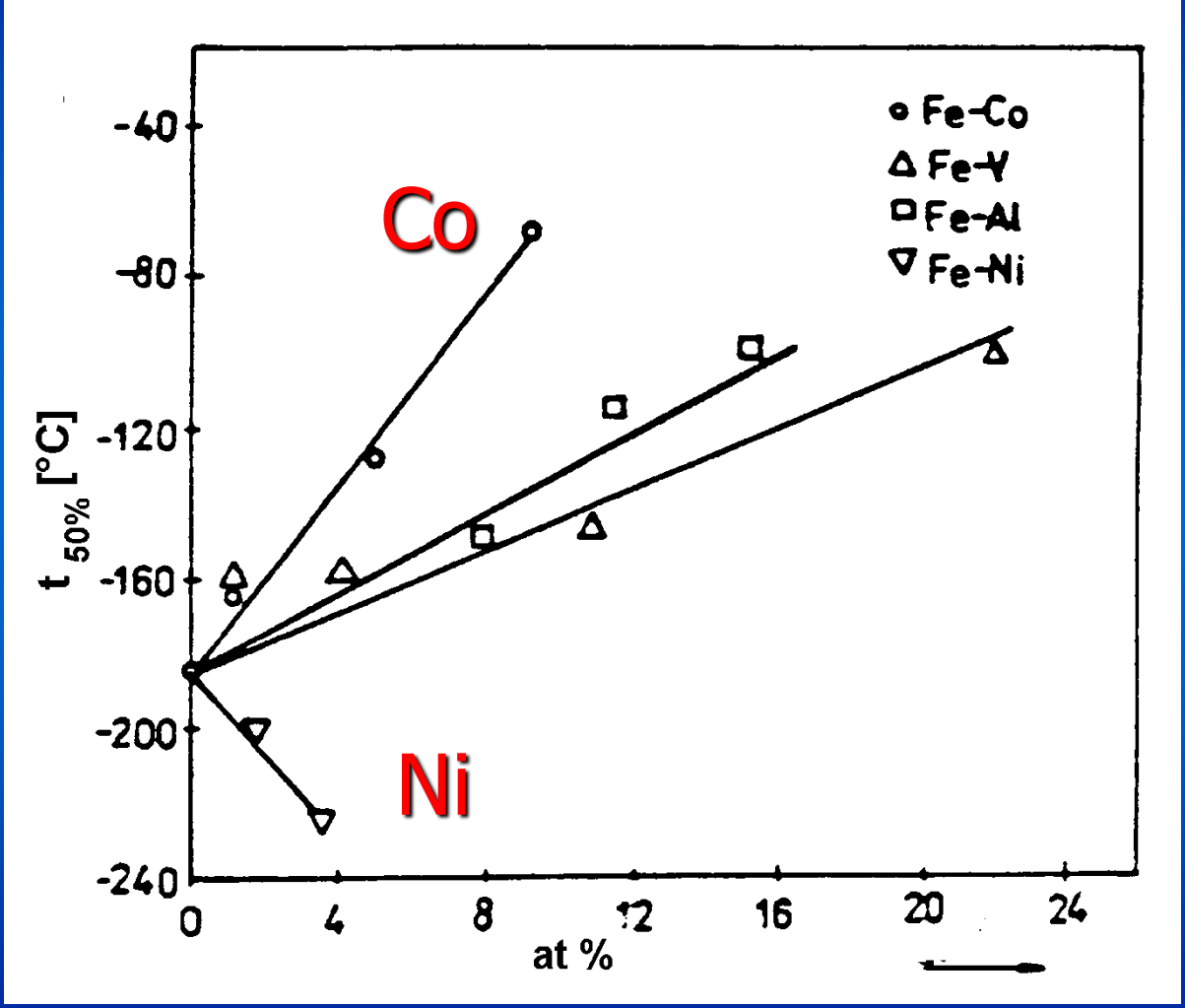
there is a small plastically deformed region, in which tensile stress is acting which higher/the same as cleavage fracture stress σ_{CF}.

Effect of microstructure on transition behaviour





Effect of alloying elements on transition behaviour



Low alloy steels for lower temperatures

- temperatures – 50°C up to – 150°C
- alloying elements 1,5% Ni, 0,15% Cr, 0,1% Mo

Highly alloyed steels for cryogenic temperatures

- -150°C up to -196°C
- Low alloy martensite

  (0,04 až 0,14) %C, (5 až 13) % Ni
- Steels of the type

  COR 13/4; 13/6 (Cr/Ni)