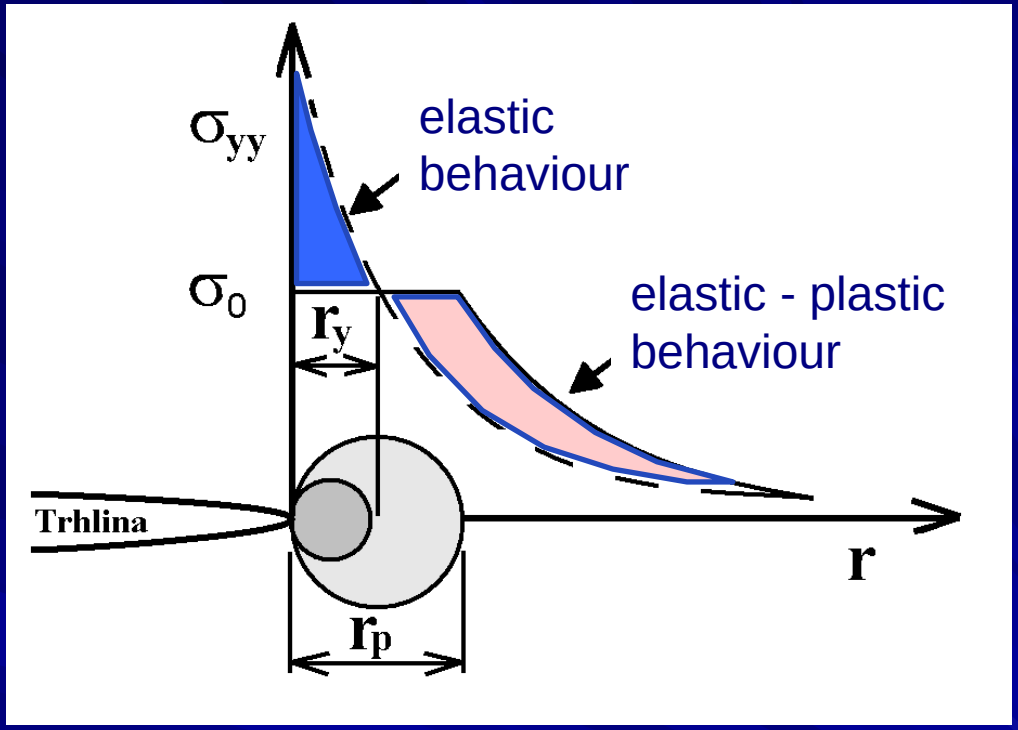
Toughness/crack resistance

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)**

Elastic solutions

$$\sigma_{yy} = R_e = \frac{K_I}{\sqrt{2\pi r_y}}$$

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



Elastic – plastic solutions

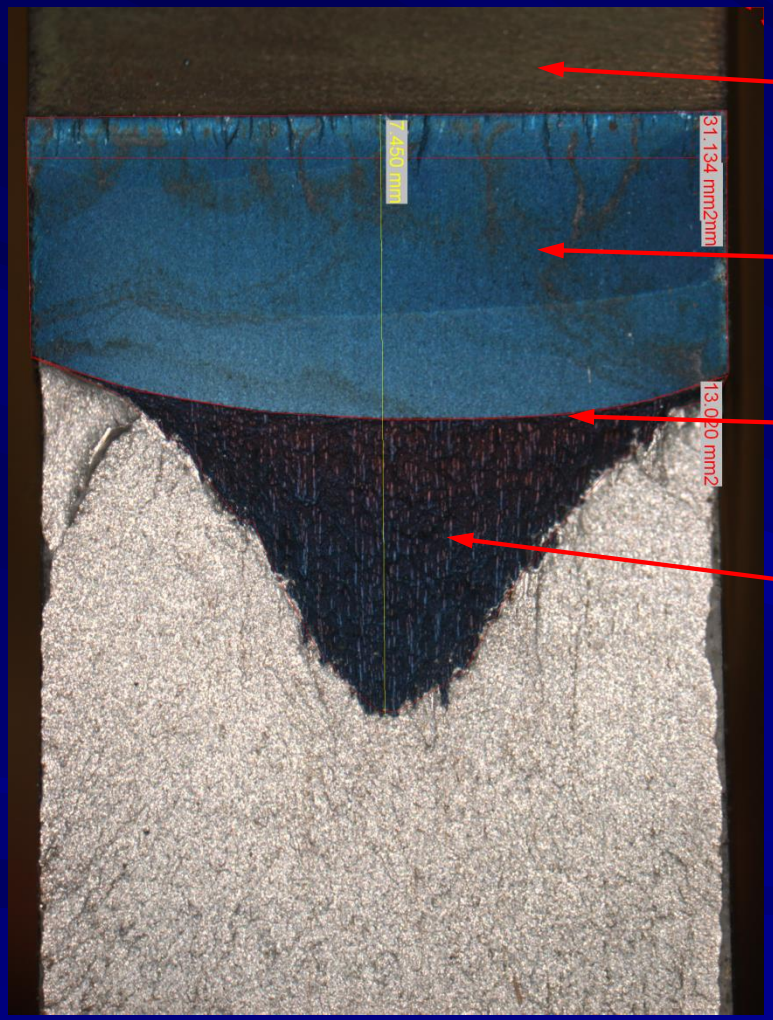
$$R_e.r_p = \int_0^{r_y}\left(\frac{K_I}{\sqrt{2\pi r_p}}\right)dr$$

$$r_p = \frac{1}{\pi}\left(\frac{K_I}{R_e}\right)$$

Plain strain condition – plastic deformation is limited by triaxial stress field

$$r_y = \frac{1}{6\pi}\left(\frac{K_I}{R_e}\right)^2$$

Elastic plastic FM J-integral



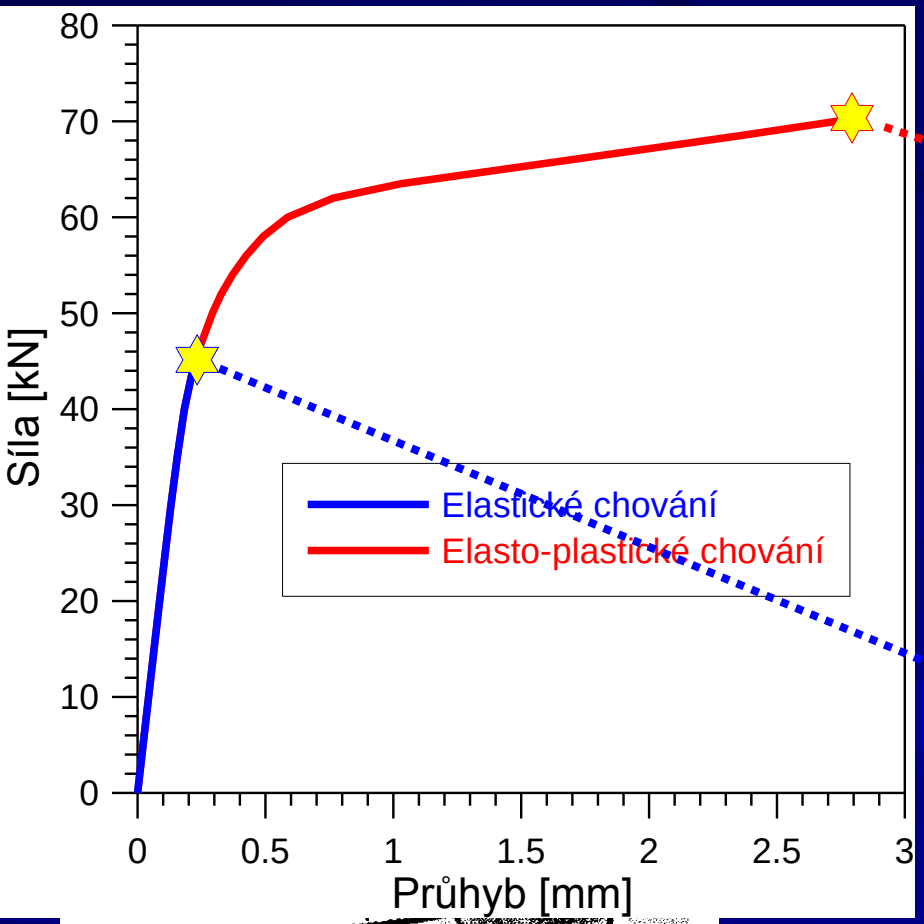
notch

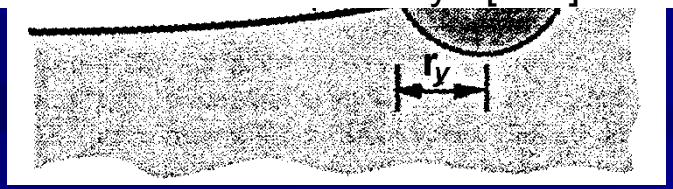
fatigue crack

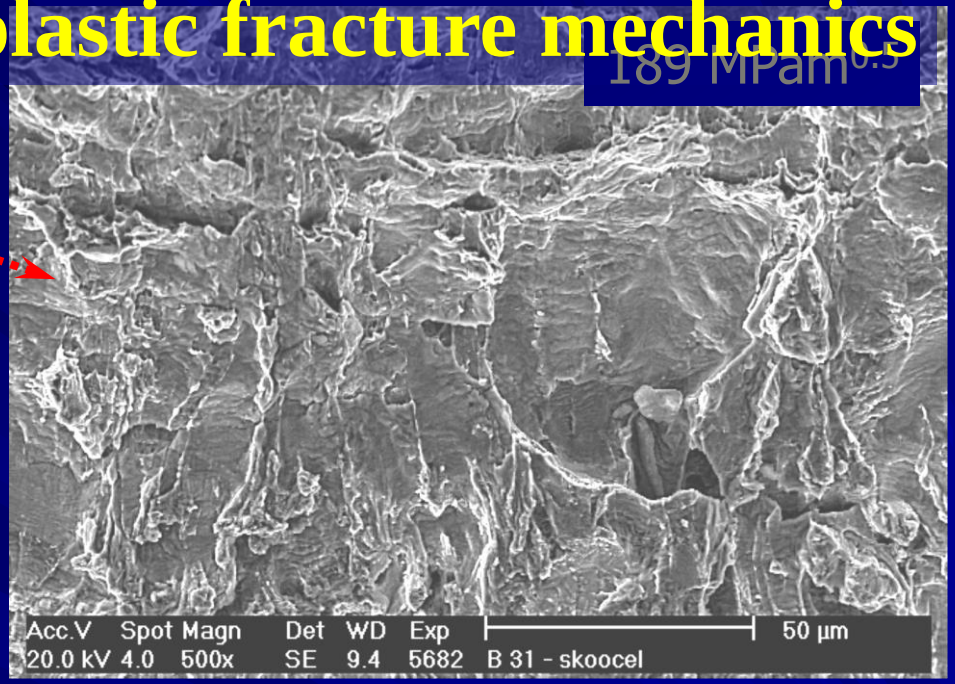
fatigue crack tip

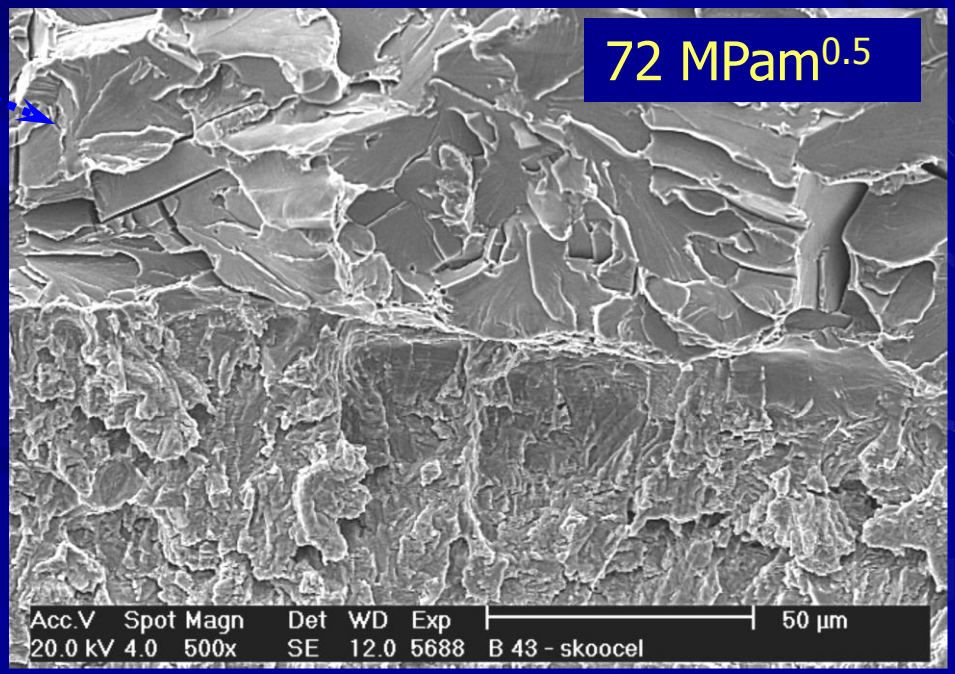
Fibrous (ductile) fracture

Elastic – plastic fracture mechanics

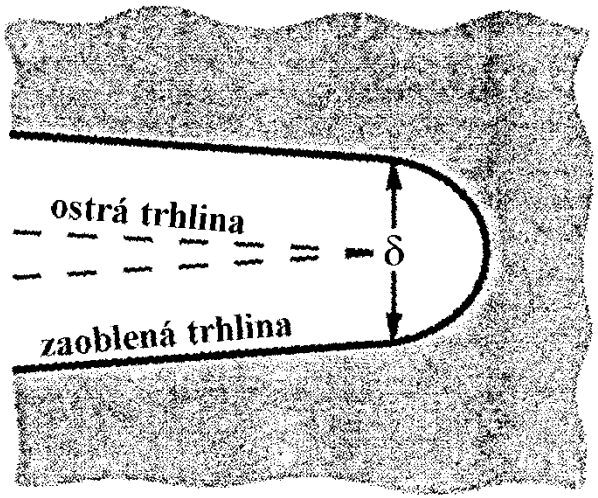


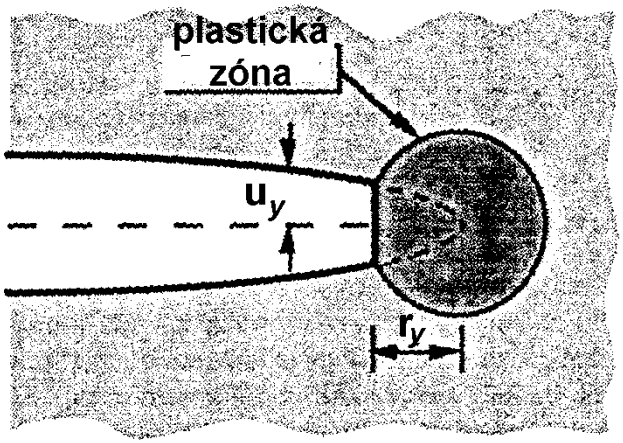






Elastic – plastic fracture mechanics





Δ, CTOD – crak tip opening displacement
fracture occurs when $\delta = \delta_c$
(materiál characteristics)

Test sample must have the same thickness as components

Elastic – plastic fracture mechanics

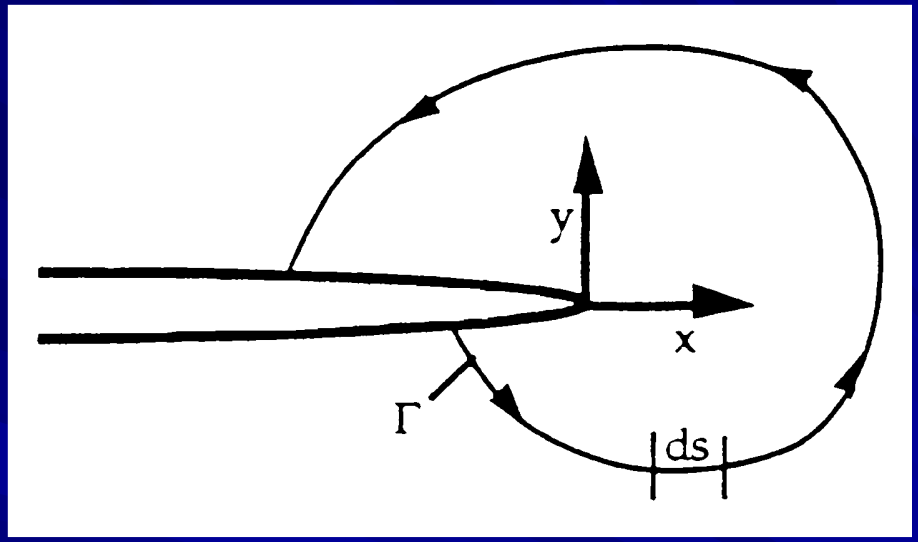
$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$

deformation energy density

$$w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$$

Components of stress vector

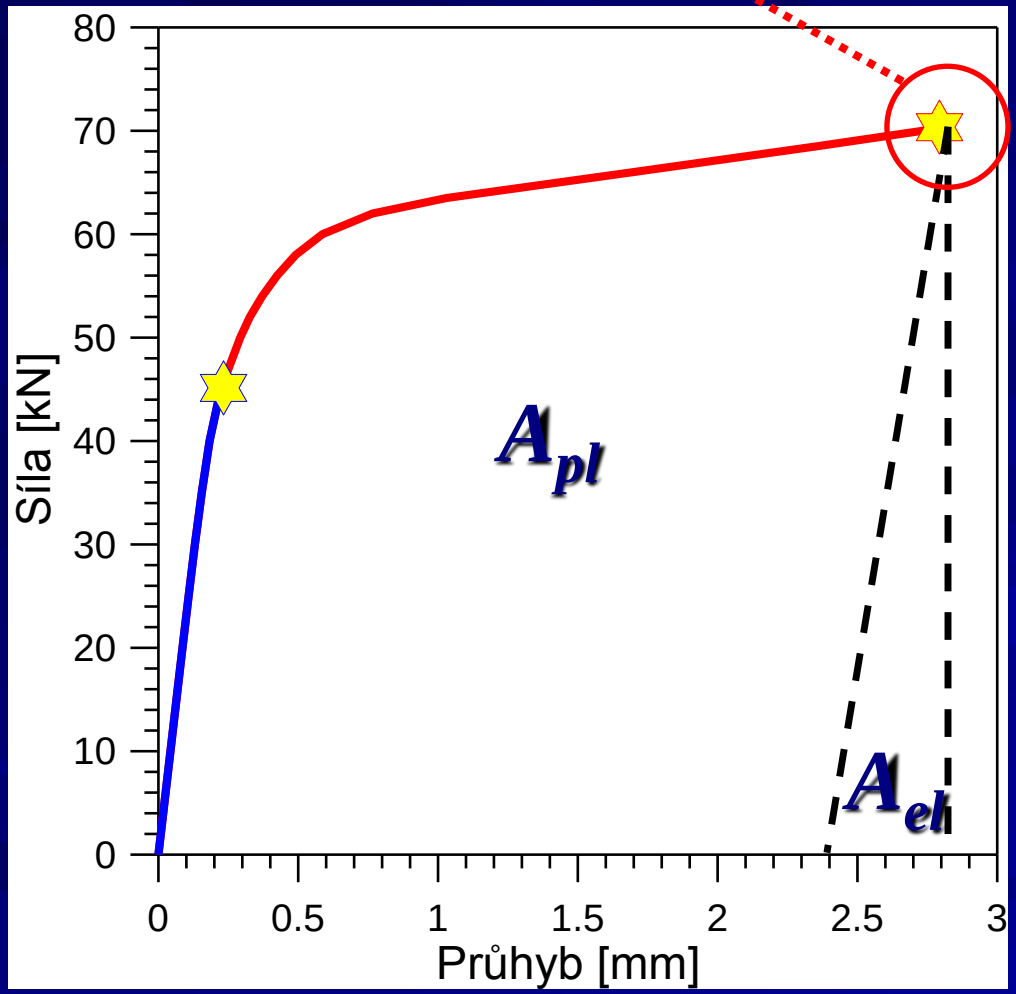
$$T_i = \sigma_{ij} n_j$$



Elastic – plastic fracture mechanics

J – integrál

J_C



$J_q = J_{el} + J_{pl}$

[kPa.m]

[kJ.m^{-2}]

RD

$$K_I = \sqrt{J_I E'}$$

$$E' = \frac{E}{1-\mu^2}$$

$$K_{JC} = \sqrt{\frac{E \cdot J_{IC}}{1-\mu^2}}$$

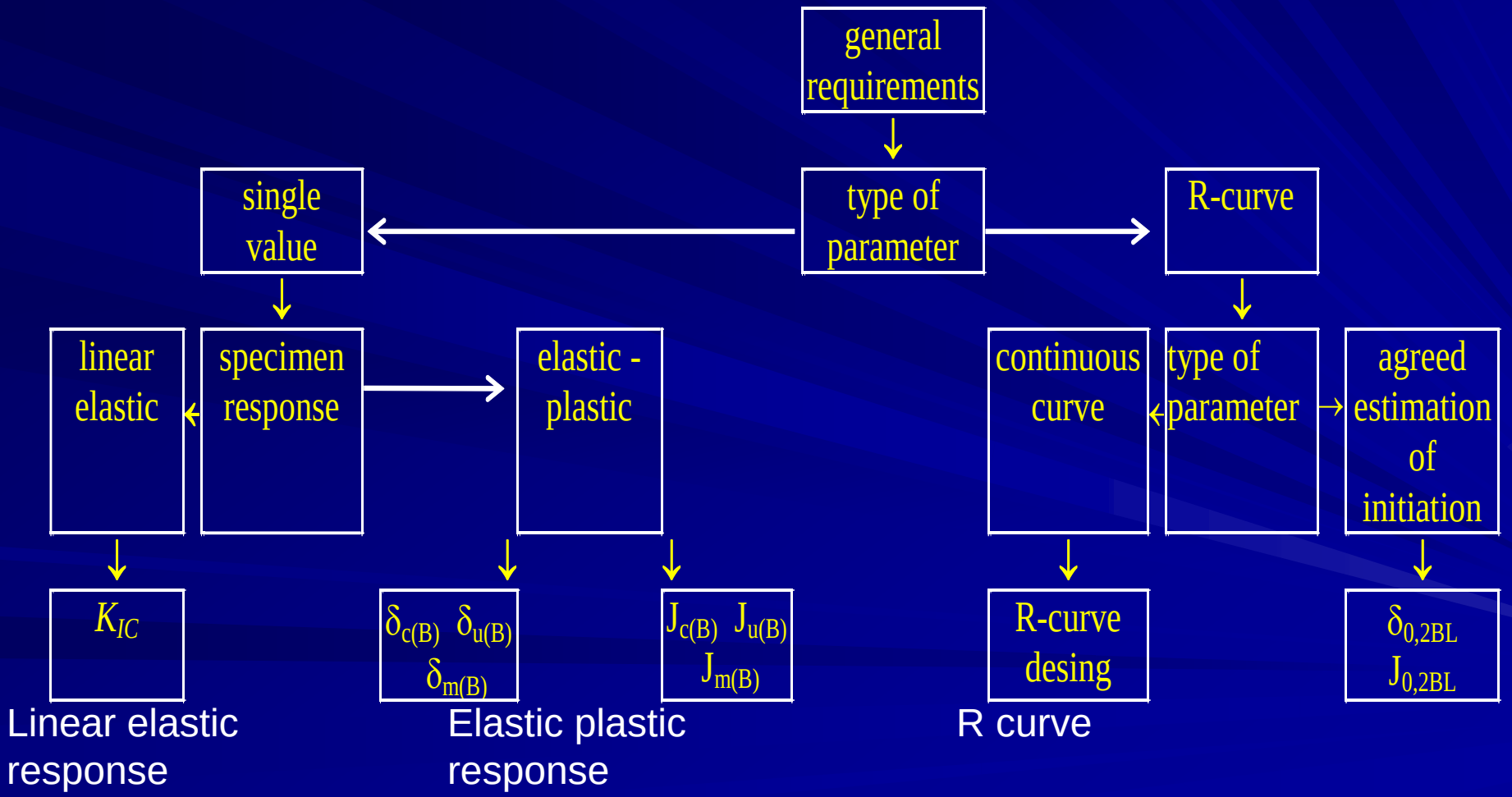
Elastic – plastic fracture mechanics

K_{Ic}	**ASTM**	**E399 - 1970**
δ_c	**BS**	**5765 – 1979**
J_c	**ASTM**	**E813 – 1981**

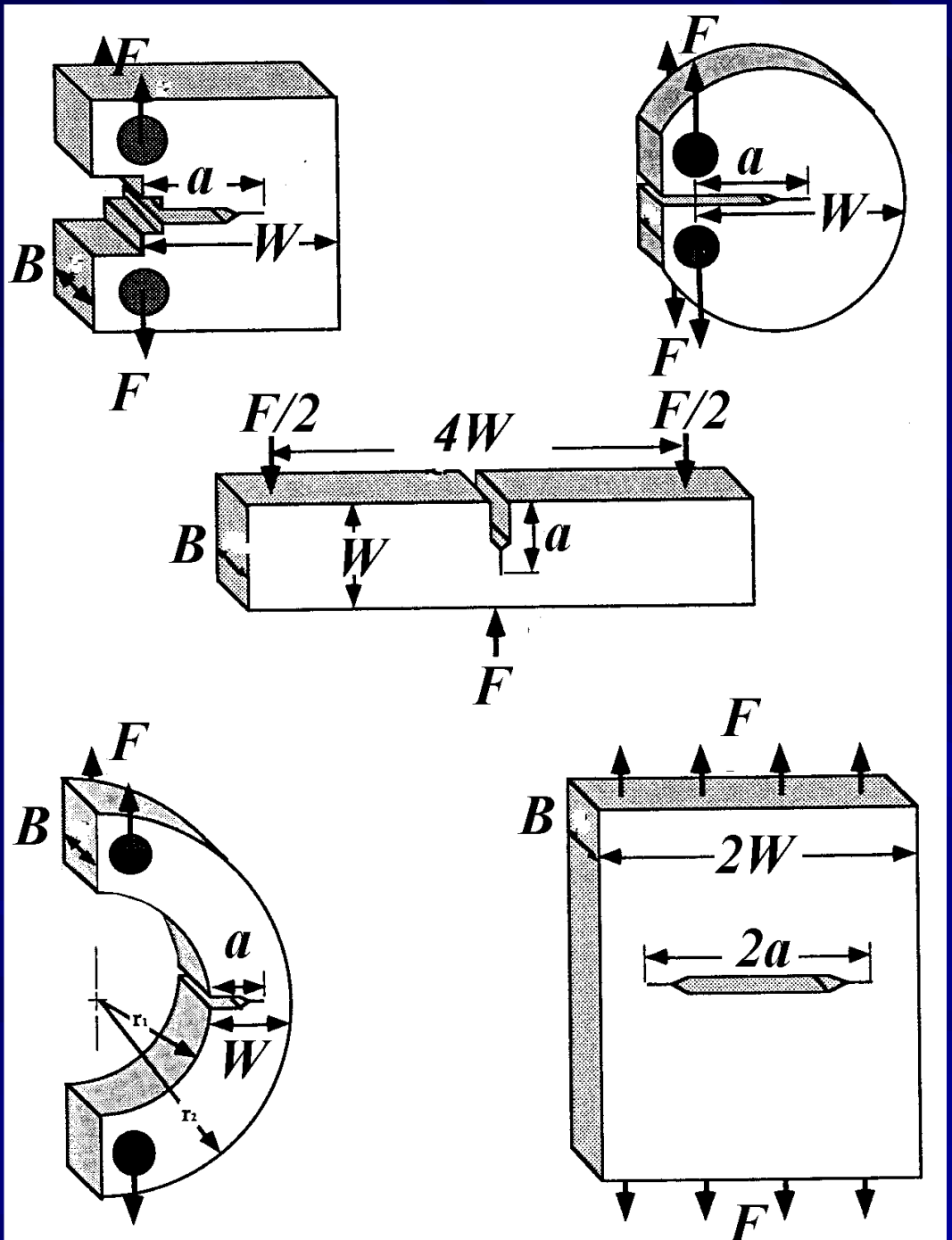
ISO 12135 – Metallic materials – unified test method for fracture toughenss determinaton

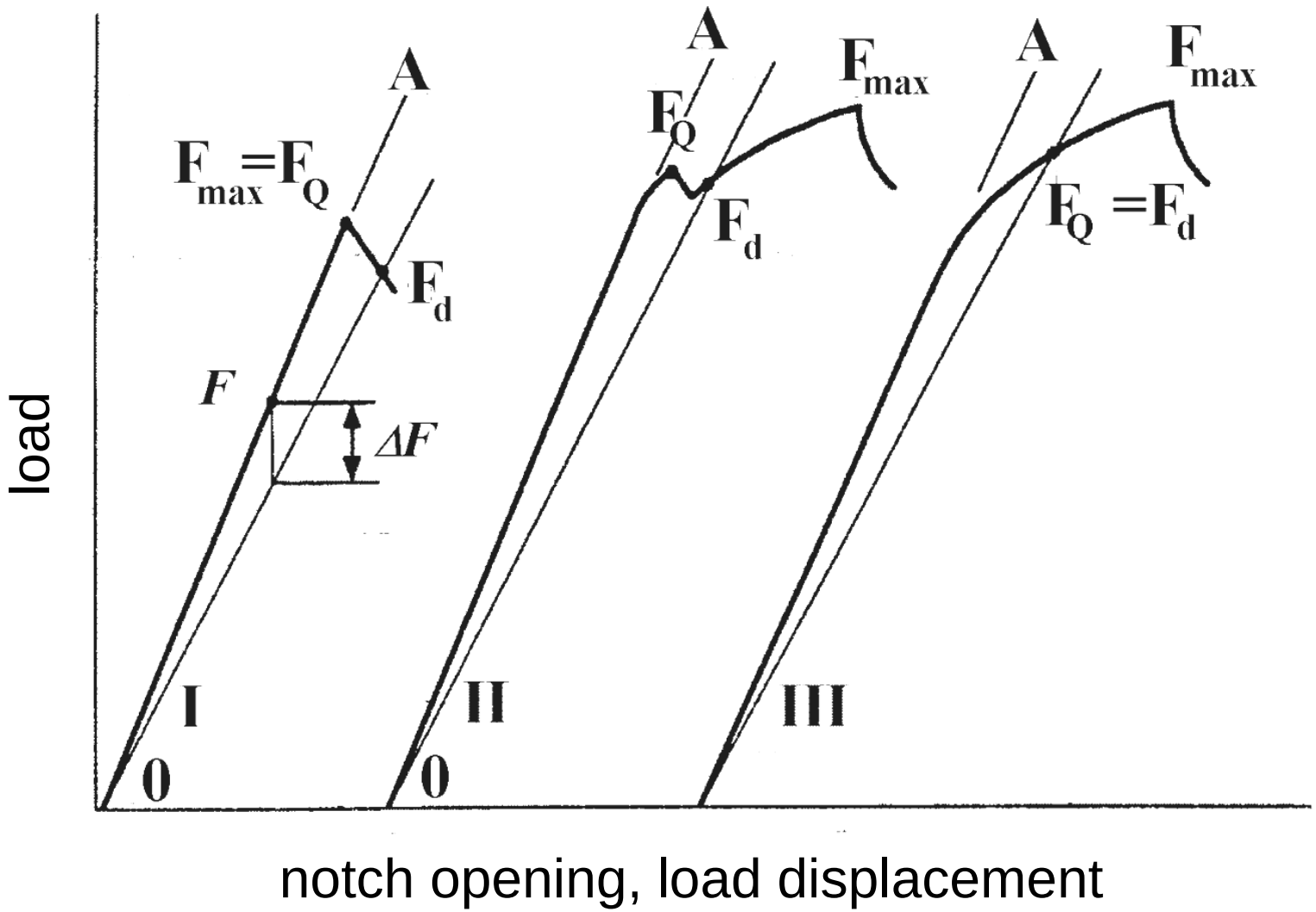
Elastic – plastic fracture mechanics

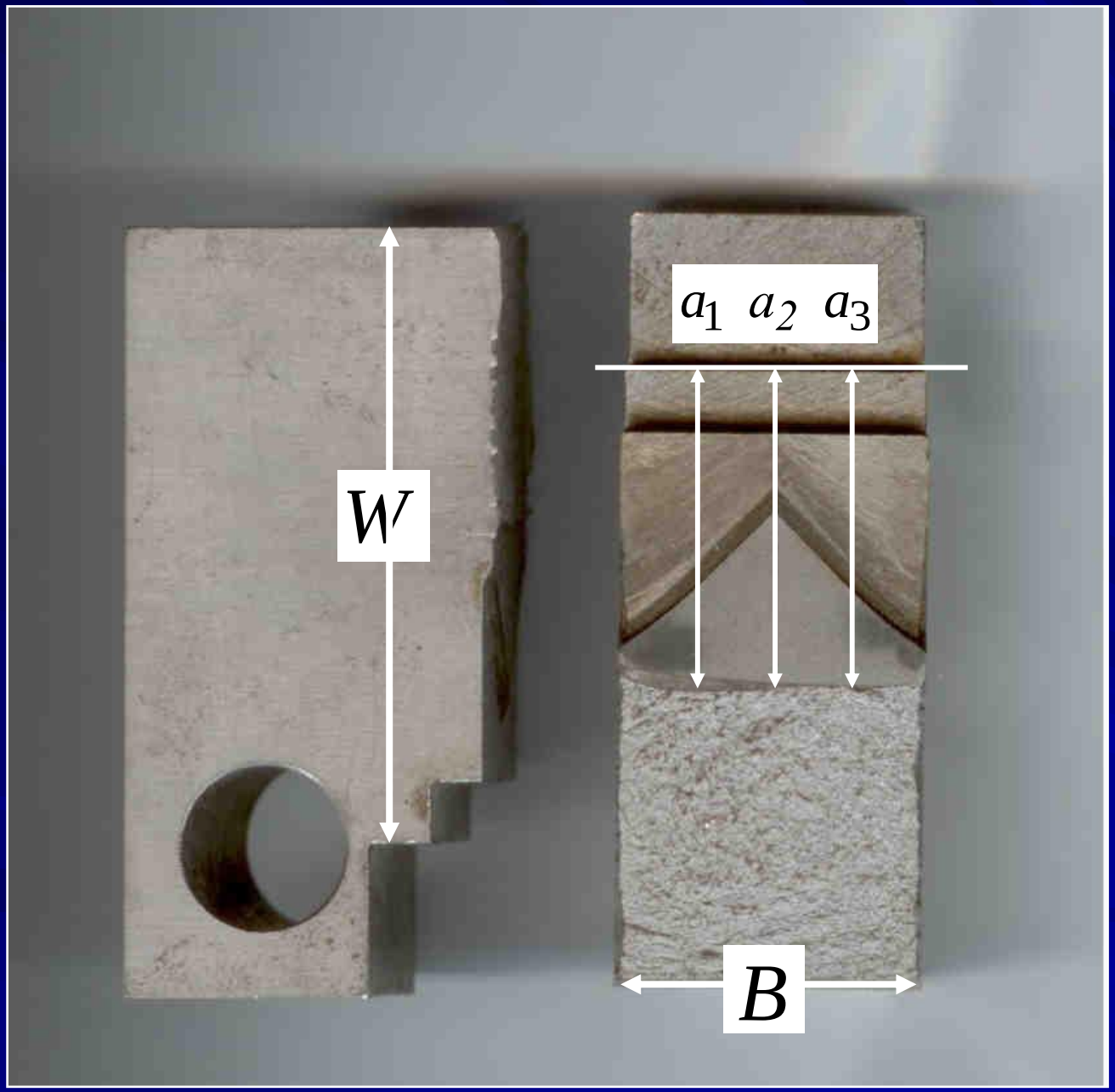
How to determine fracture toughness ?



Linear elastic FM




load
A
$F_{max}=F_Q$
F_d
F
ΔF
I
0
A
F_Q
F_{max}
F_d
II
0
A
F_{max}
$F_Q=F_d$
III
notch opening, load displacement


a_1 a_2 a_3
W
B

LELM

$$K_Q = \frac{F_Q}{B\sqrt{W}} g\left(\frac{a}{W}\right);$$

K_Q provisional (question) value of fracture toughness

validity condiitons

$$K_f \le 0{,}6 K_Q \frac{R_e(T_1)}{R_e(T_2)}$$

$$F_{max} \le 1{,}1 F_Q$$

$$a, B, (W - a) \ge 2{,}5\left(\frac{K_Q}{R_e}\right)^2$$

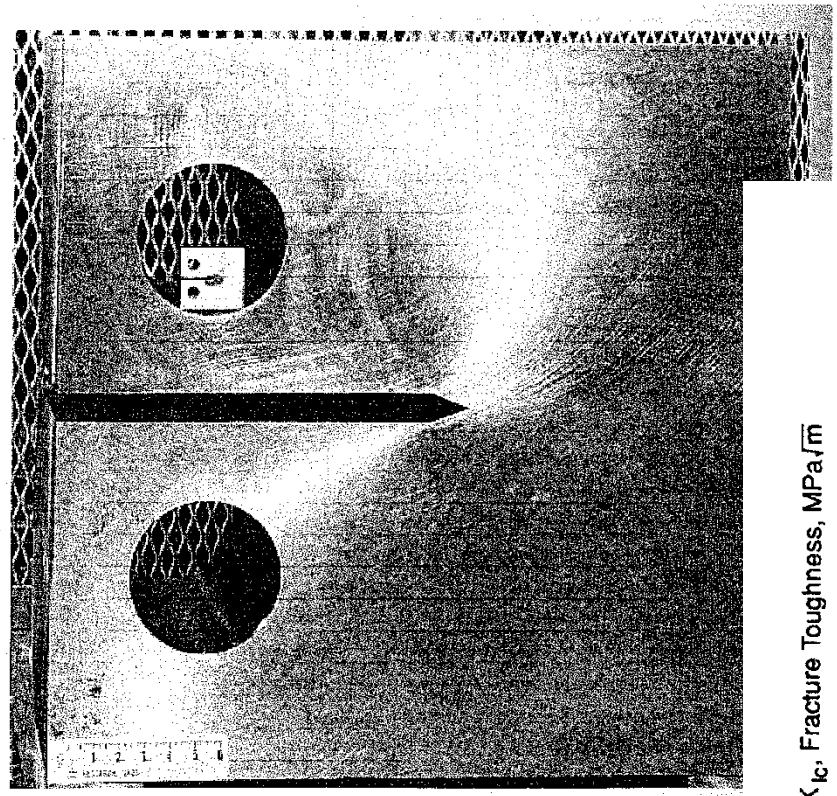
$$K_Q \equiv K_{IC}$$

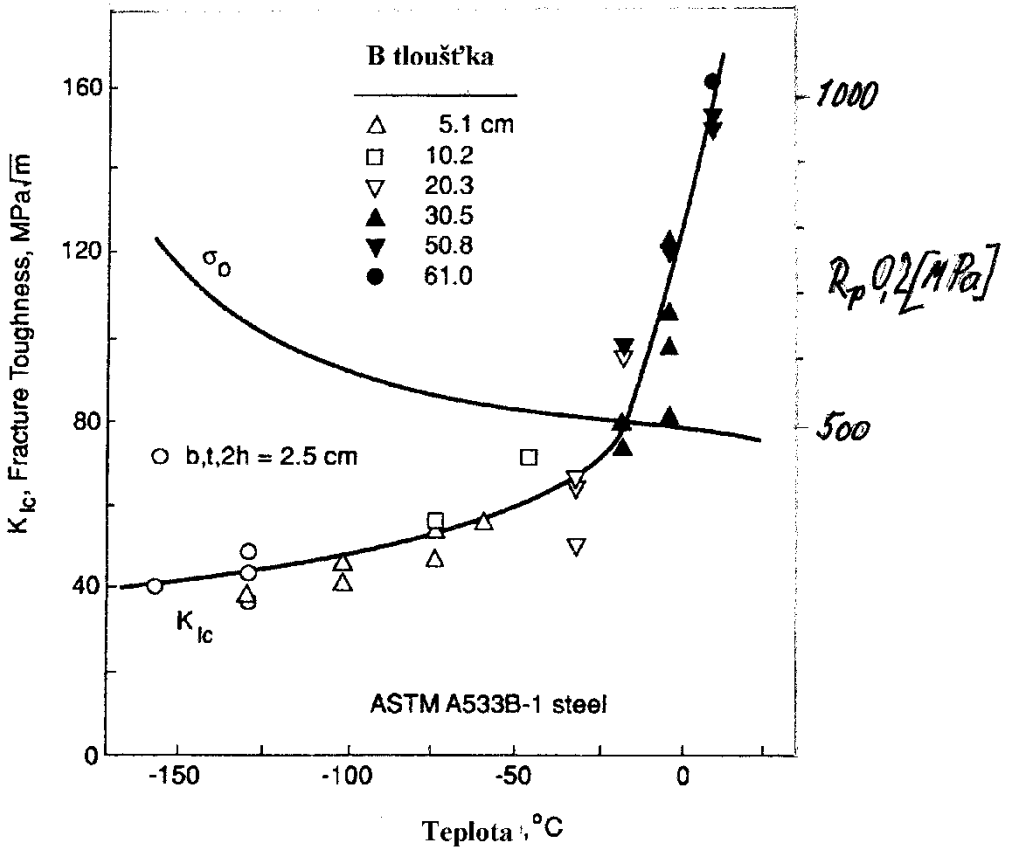
qualification procedures

$$K_Q \equiv K_{IC}, K_C, K_{JC}, K_{JC(Q)}, K_{Ji}, K_{Jm}$$

Fracture toughness determination

LELM

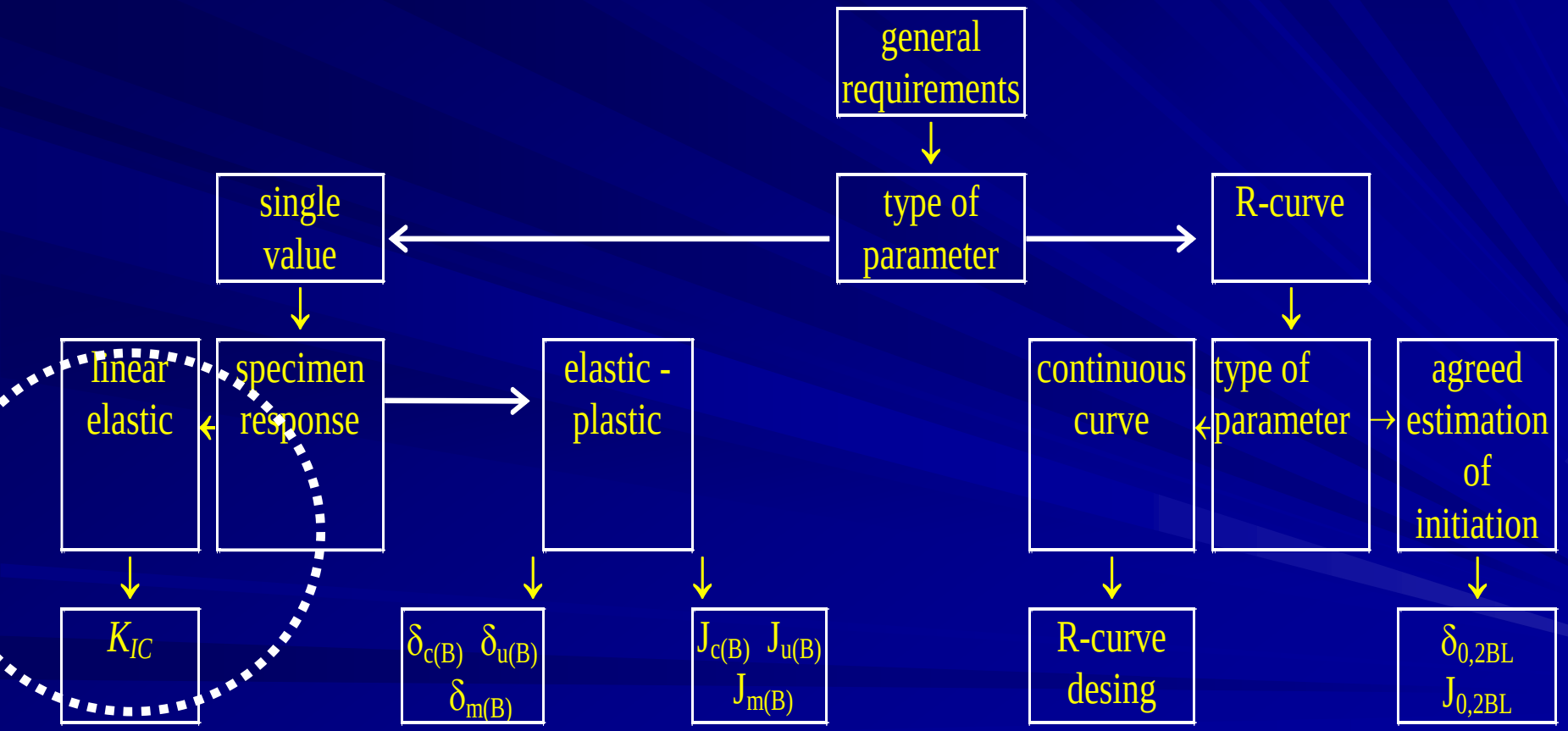




Elastic – plastic fracture mechanics

one value
r curve

How to determine fracture toughness ?



Linear elastic response

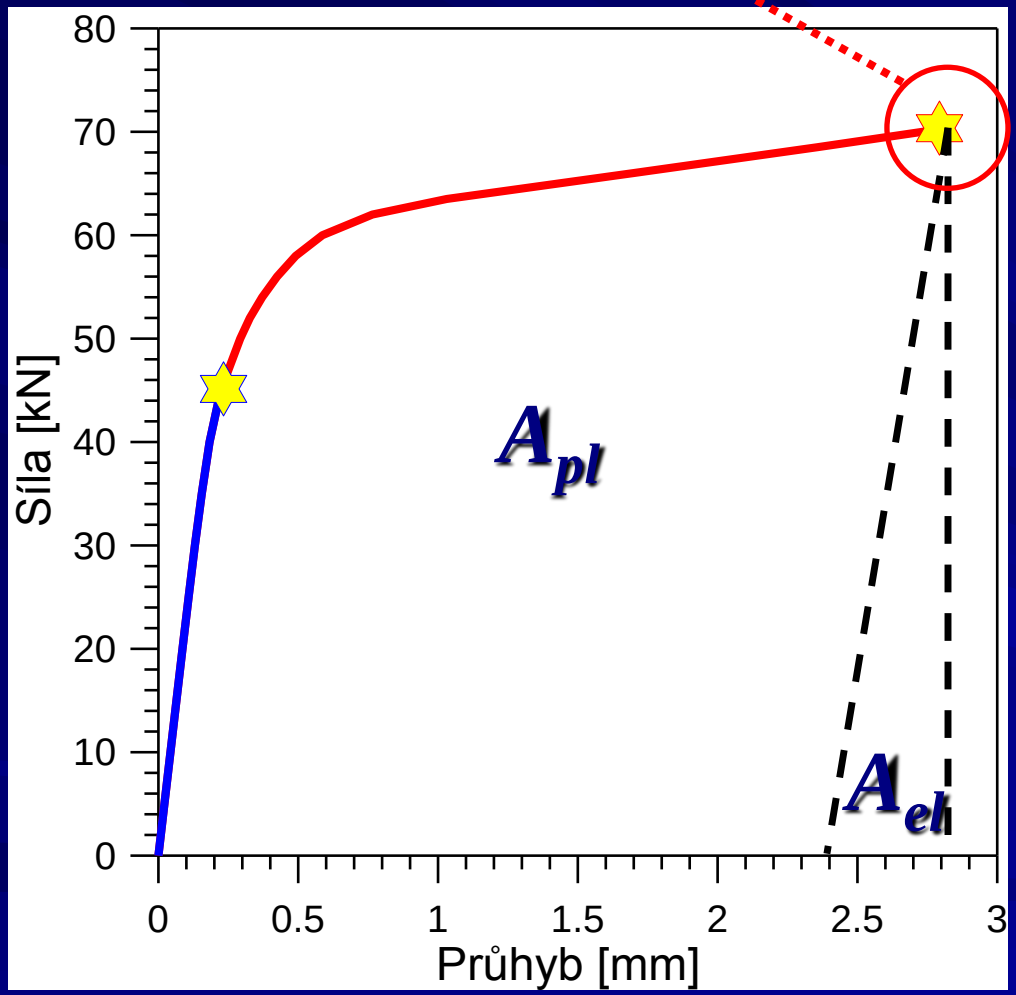
Elastic plastic response

R curve

J integral determination

EPFM

J – integral



$$J_Q = J_{el} + J_{pl}$$

$$J_e = \frac{1-\mu^2}{E} K^2$$

$$J_p = \frac{A_{pl} f\left(\frac{a}{W}\right)}{B(W-a)}$$

$J_q = J_{el} + J_{pl}$

EPFM

$$J_e = \frac{1-\mu^2}{E}K^2 \qquad J_p = \frac{A_{pl} f\left(\frac{a}{W}\right)}{B(W-a)}$$

Validity condition

$$a; B(W-a) \geq 50\,\frac{J_{IC}}{R_e + R_m}$$

$$K_{JC} = \sqrt{\frac{E \cdot J_{IC}}{1-\mu^2}}$$

$$K_{JC(limit)} = \sqrt{\frac{E * b * R_p 0{,}2}{50}}$$

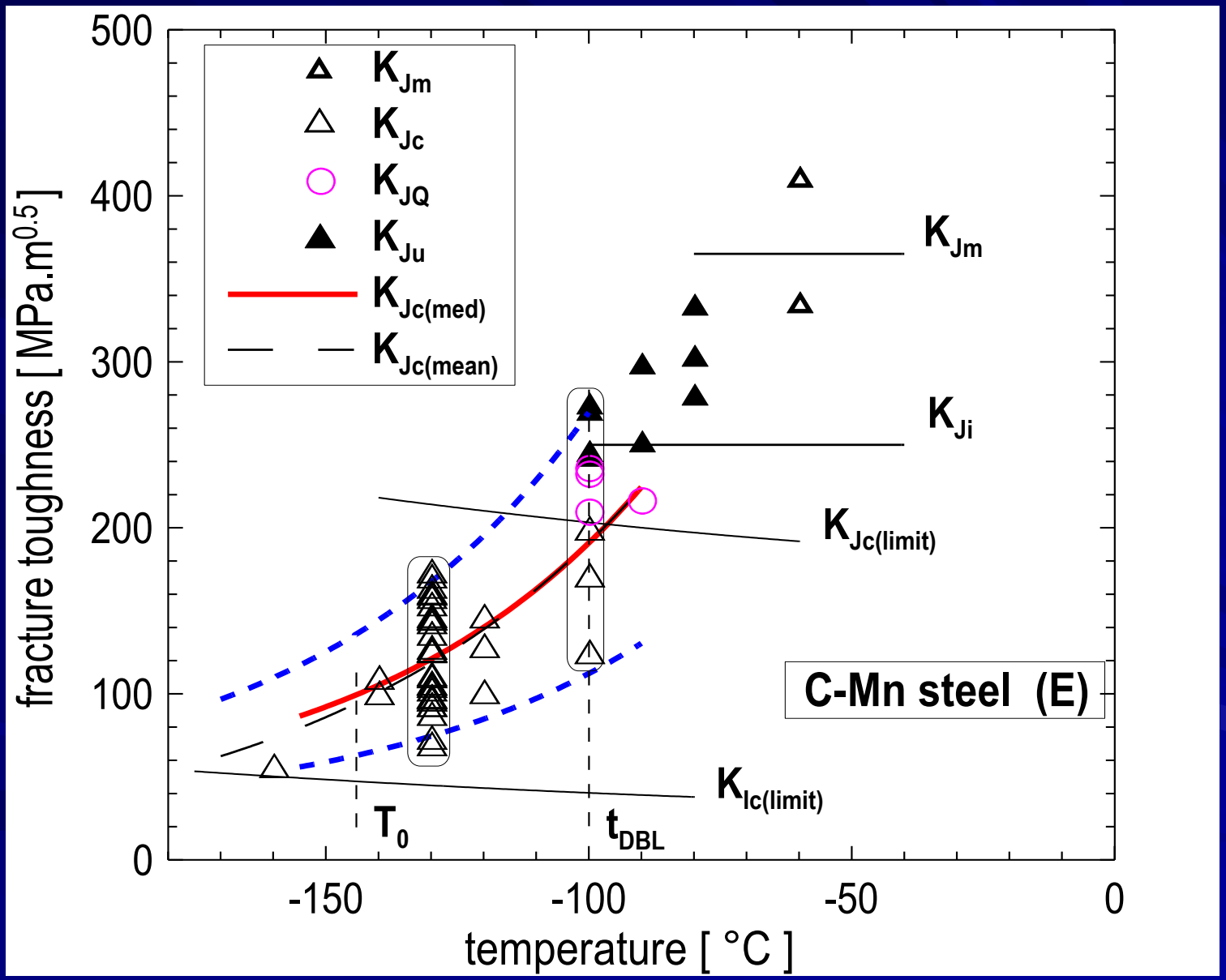
$$J = \left[\frac{4F}{B.\sqrt{W}}\, g_1\left(\frac{a}{W}\right)\right]^2 \left[\frac{\left(1-\mu^2\right)}{E}\right] + \frac{2A_{pl}}{B(W-a)}$$

SENB

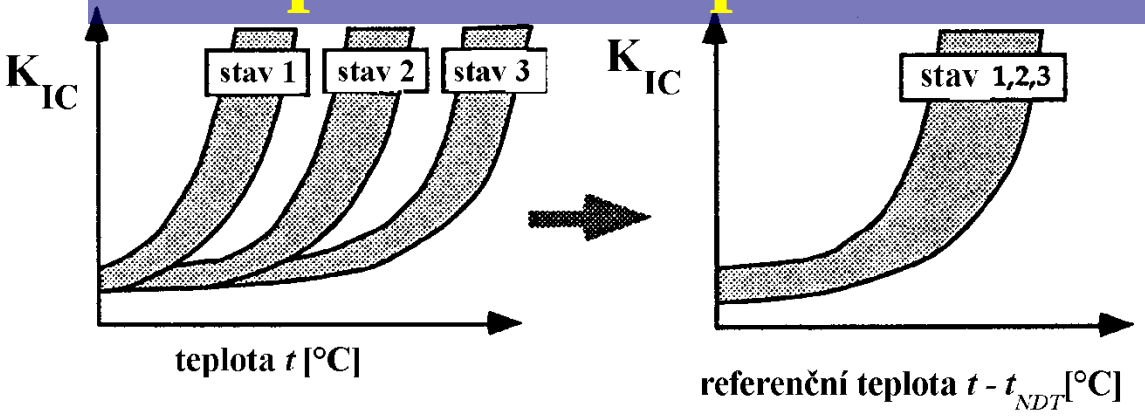
$$J = \frac{1-\mu^2}{E}K_{IC}{}^2 + \frac{\left[2 + 0{,}522\left(1-\frac{a}{W}\right)\right]A_{pl}}{B(W-a)}$$

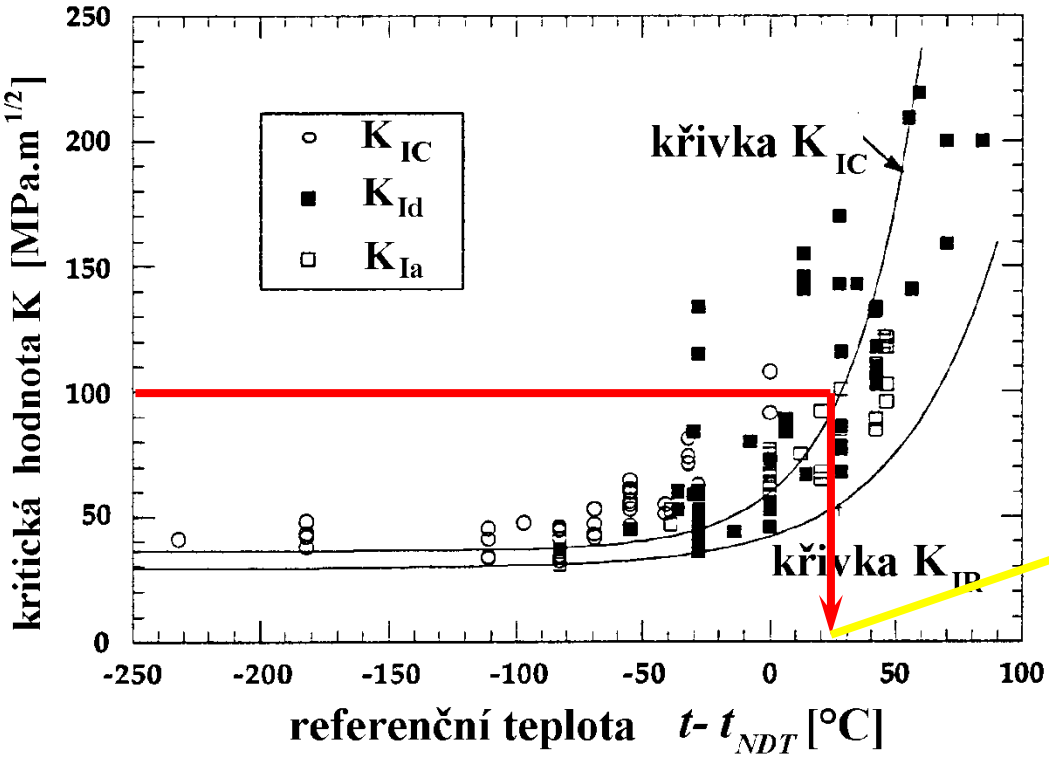
CT

temperature dependence of fracture toughness



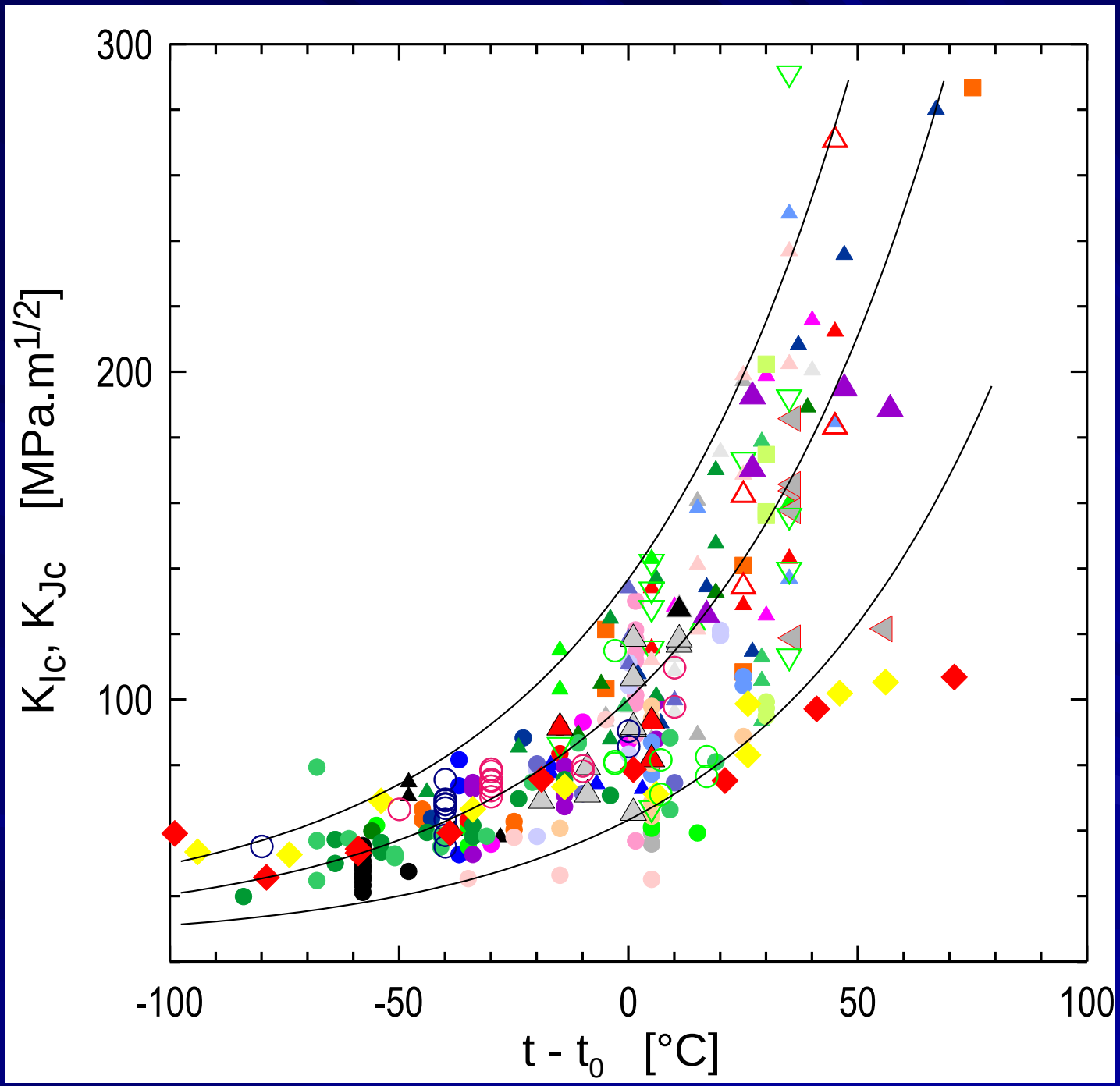
temperature dependence of fracture toughness



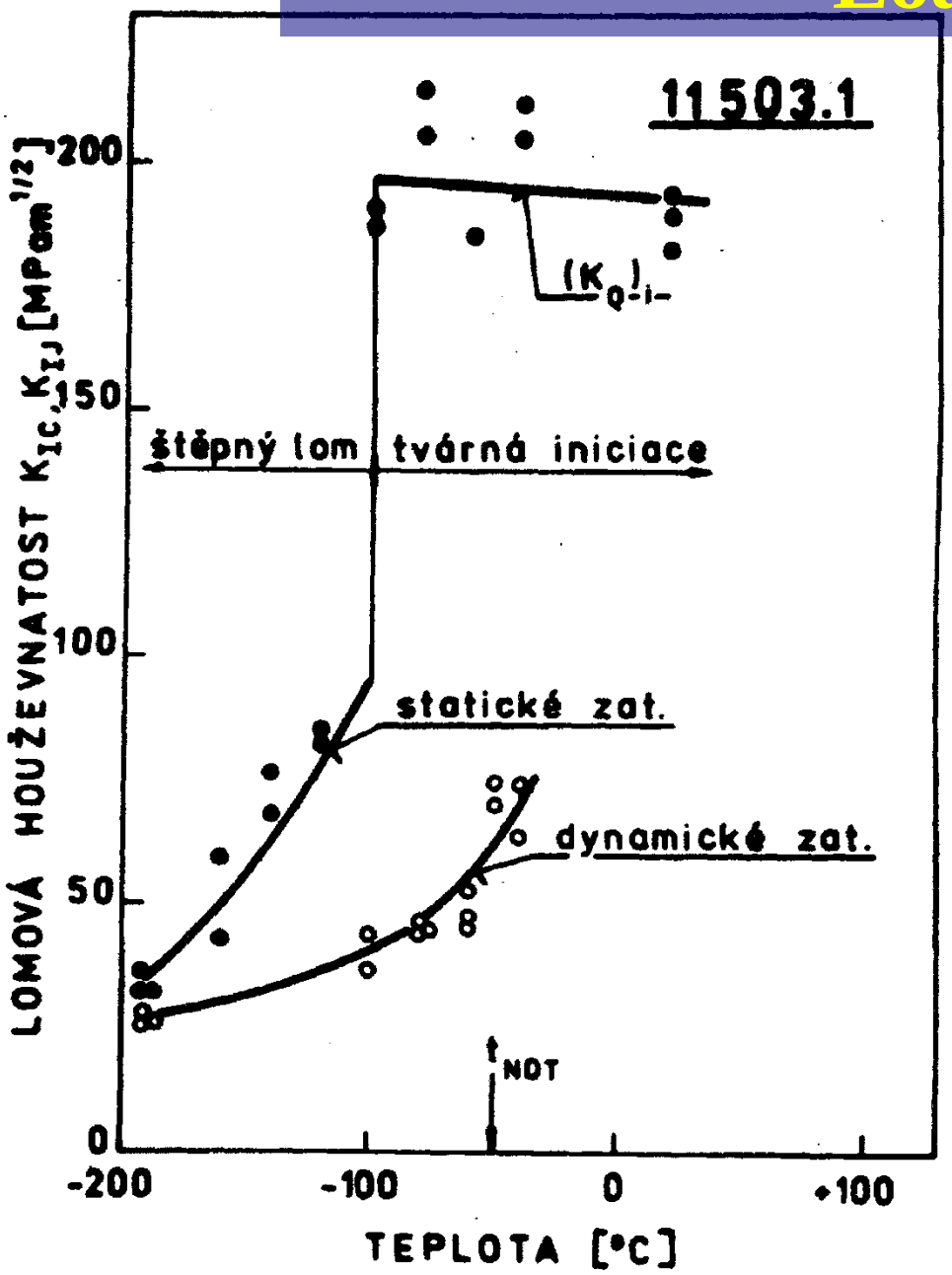


master curve

T_0


300
200
100
K_{Ic}, K_{Jc} [MPa.m$^{1/2}$]
-100
-50
0
50
100
t - t_0 [°C]

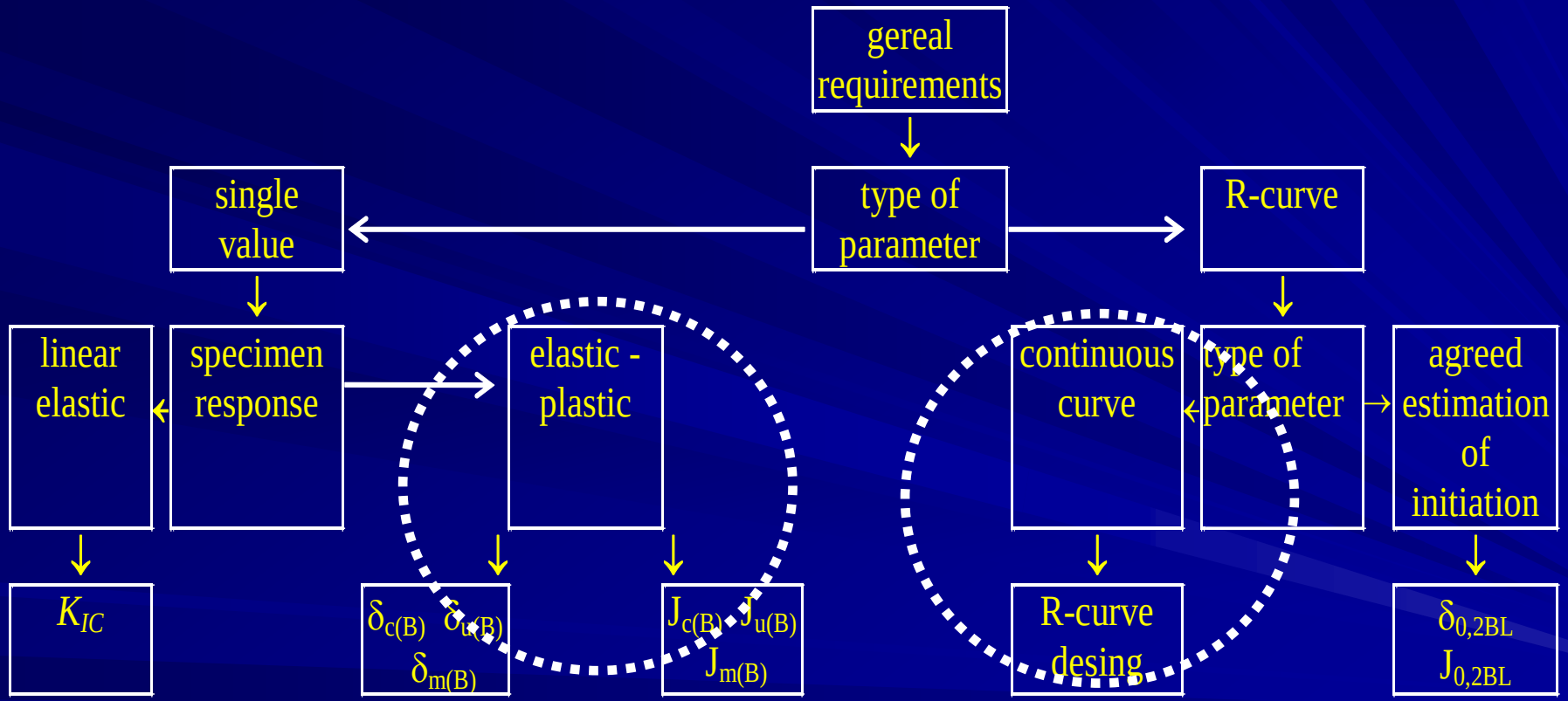
Loading rate effect on K_{Ic}



temperature and loading rate effect

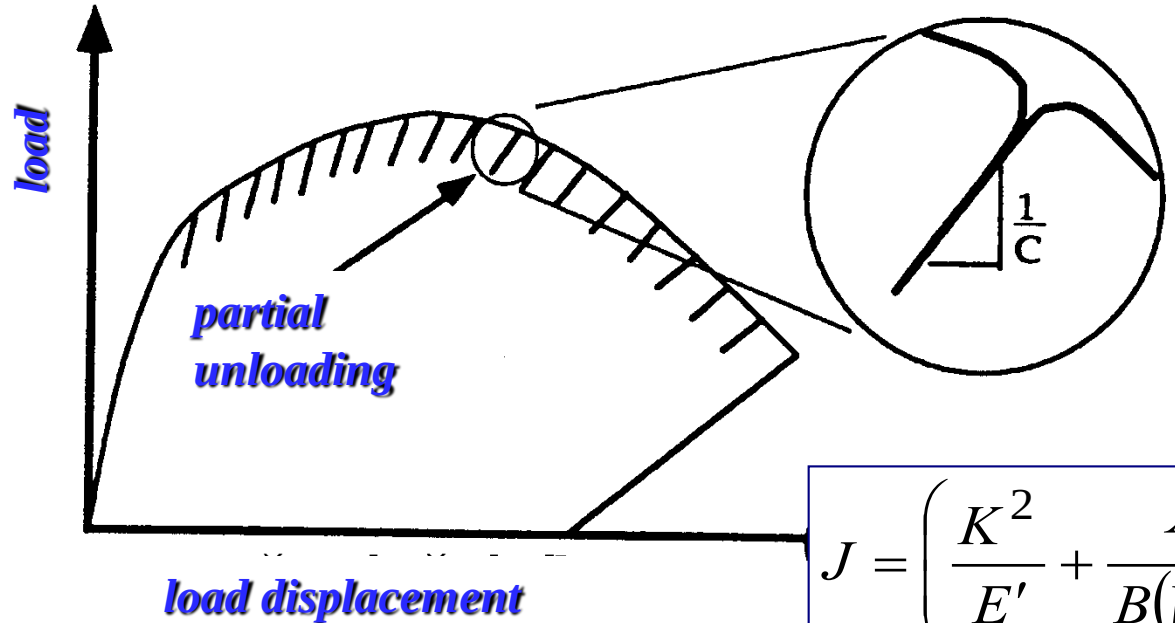
Elastic – plastic fracture mechanics

Fracture toughness determination ?



J_R (J-Δa) curve determination

Single specimen method



$$J = \left(\frac{K^2}{E'} + \frac{X_i A_p}{B(W - a_0)} \right) \left(1 - \frac{\Delta a}{2(W - a_0)} \right)$$

J_R (J-Δa) curve determination