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Influence of loading rate on fracture mechanics properties

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Influence of Loading Rate on Fracture Mechanics Properties

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Joint ICTP/IAEA Workshop

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Outline

- Loading rate effects on the fracture toughness of steels
  - fully and partially brittle behaviour
  - fully ductile behaviour
- Estimation of the loading rate in a fracture toughness test
- Experimental determination of fracture toughness at elevated loading rates:
  - existing official standards (ASTM and ISO)
  - applicability of the Master Curve approach to impact test data from precracked Charpy specimens
  - latest revision of ASTM E1921 (2009)
  - new ISO standard/annex to ASTM E1820 in preparation
    - experimental procedure
    - dynamic evaluation of fracture toughness (fully brittle situations)
    - crack resistance curves by multiple and single-specimen methods
  - tensile properties to be used in the analyses
- Some experimental results

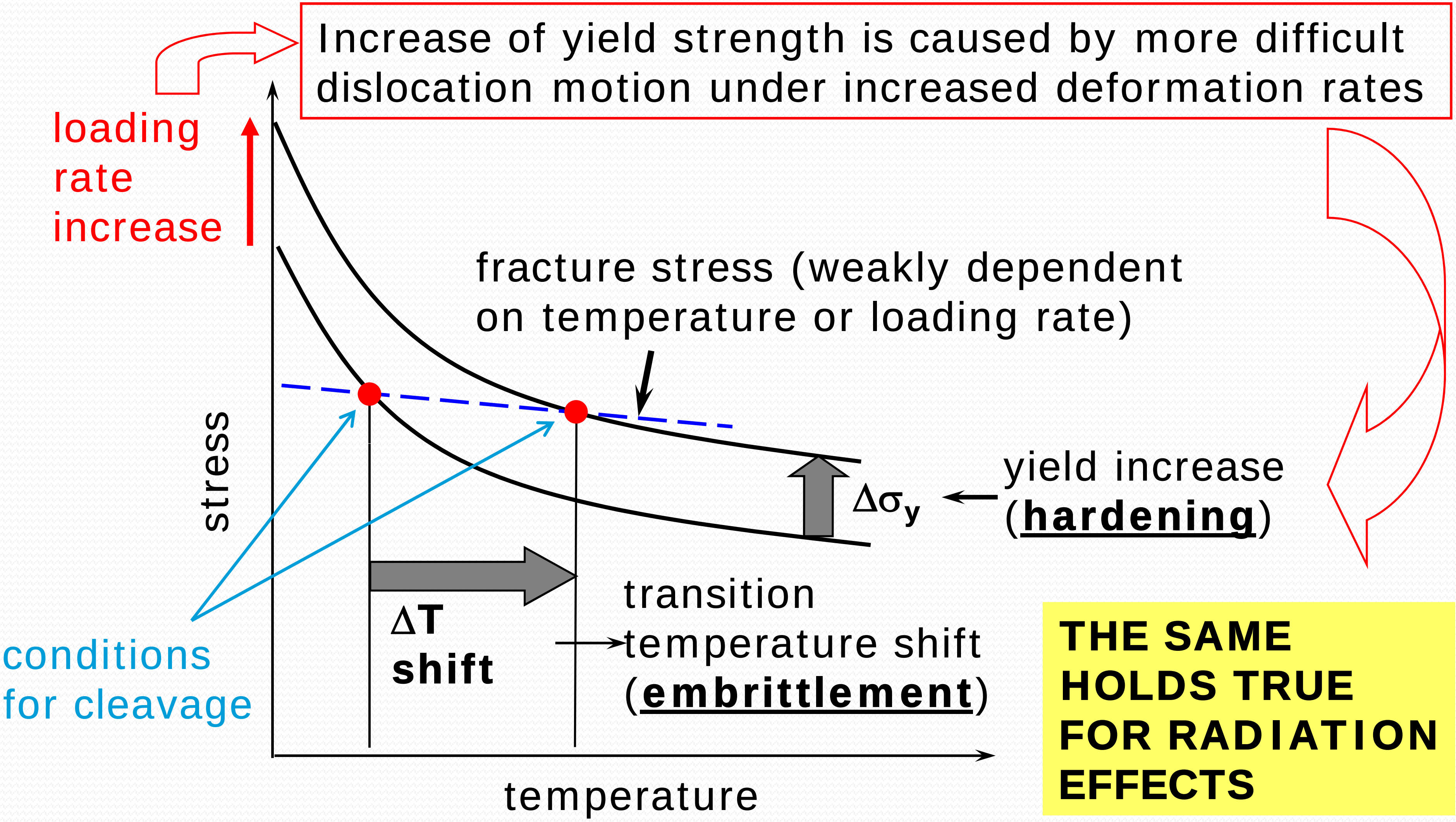
How does increasing loading rate influence fracture toughness?

- <u>Lower shelf</u> (*fully brittle behavior*): toughness decreases with loading rate ⇨ $\boxed{K_{Id} < K_{Ic}}$
- <u>Ductile-to-brittle transition regime</u> (*mixed brittle/ductile behavior*): transition/reference temperature increases with loading rate

  ⇨ $\boxed{T_{o,dyn} > T_{o,st}}$
- <u>Upper shelf</u> (*fully ductile behavior*): toughness (initiation/propagation) increases with loading rate

  ⇨ $\boxed{J_{Id} > J_{Ic}}$

Why does an increase in loading rate make a steel *more brittle*?

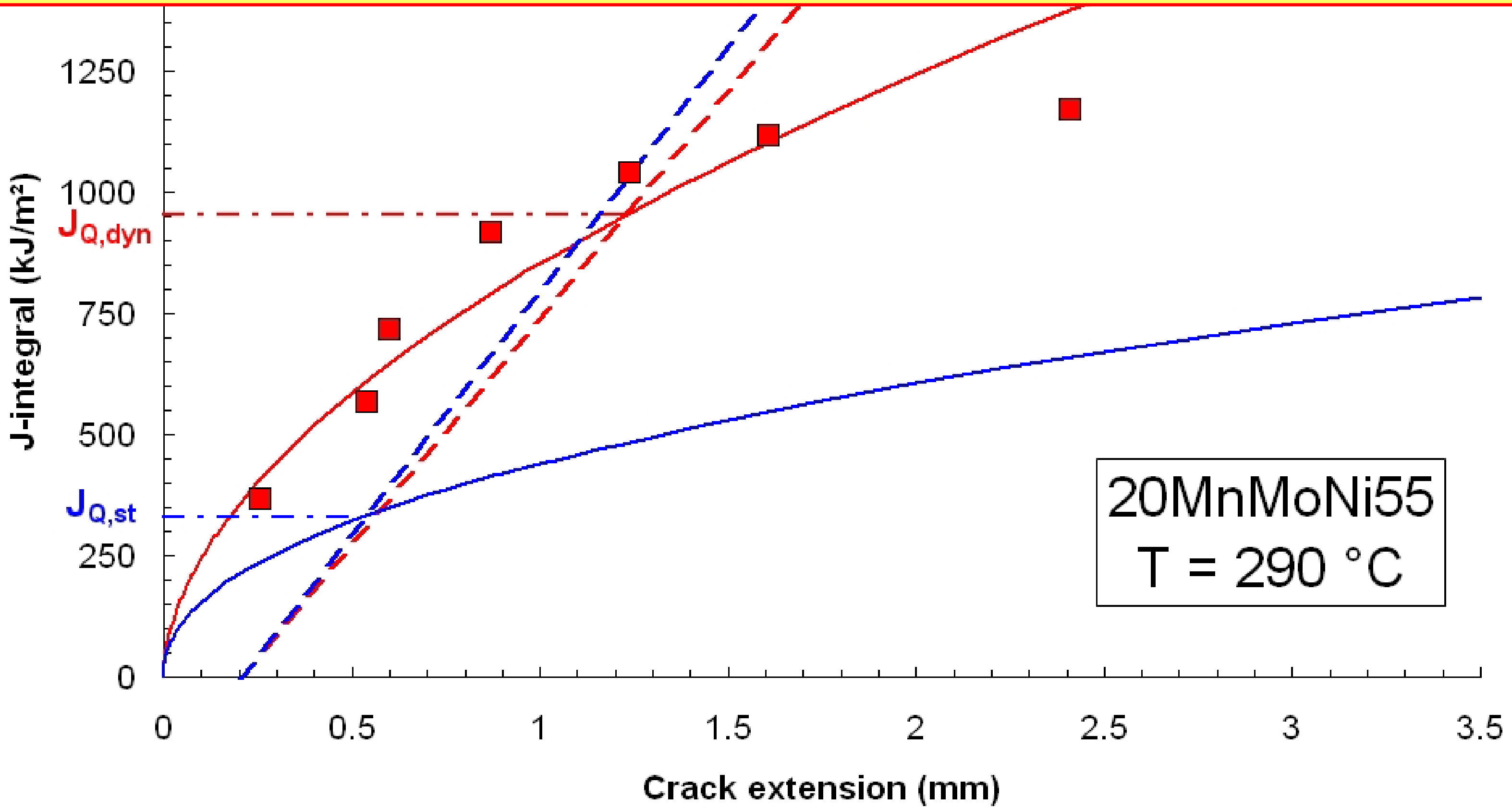


Increase of yield strength is caused by more difficult dislocation motion under increased deformation rates

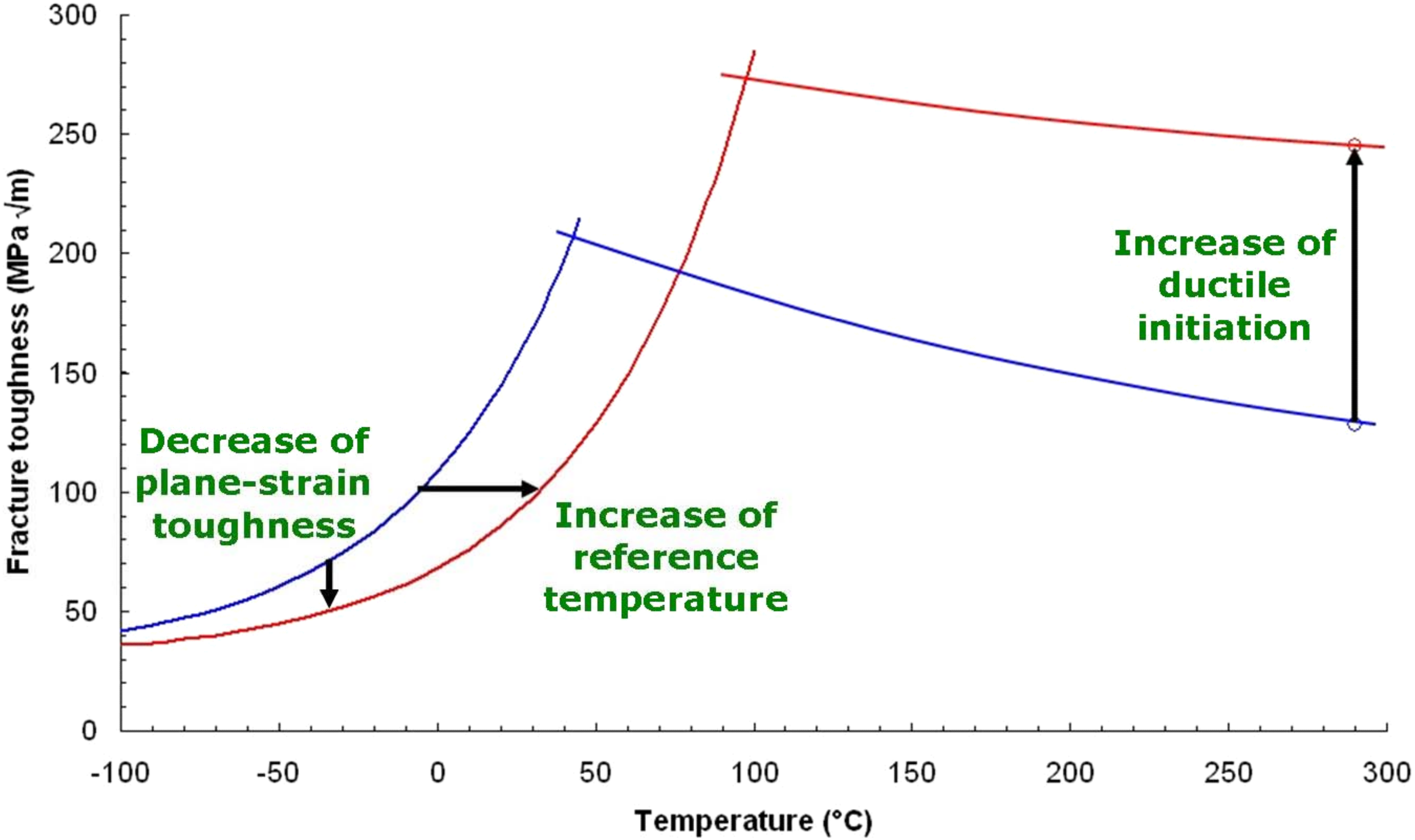
THE SAME HOLDS TRUE FOR RADIATION EFFECTS

Why does an increase in loading rate make a steel *more ductile*?

Dislocation motion is more difficult → material plastic deformation is hindered → void nucleation, growth and coalescence takes place at increased work levels → toughness is higher



Overall effect of loading rate increase on steel toughness

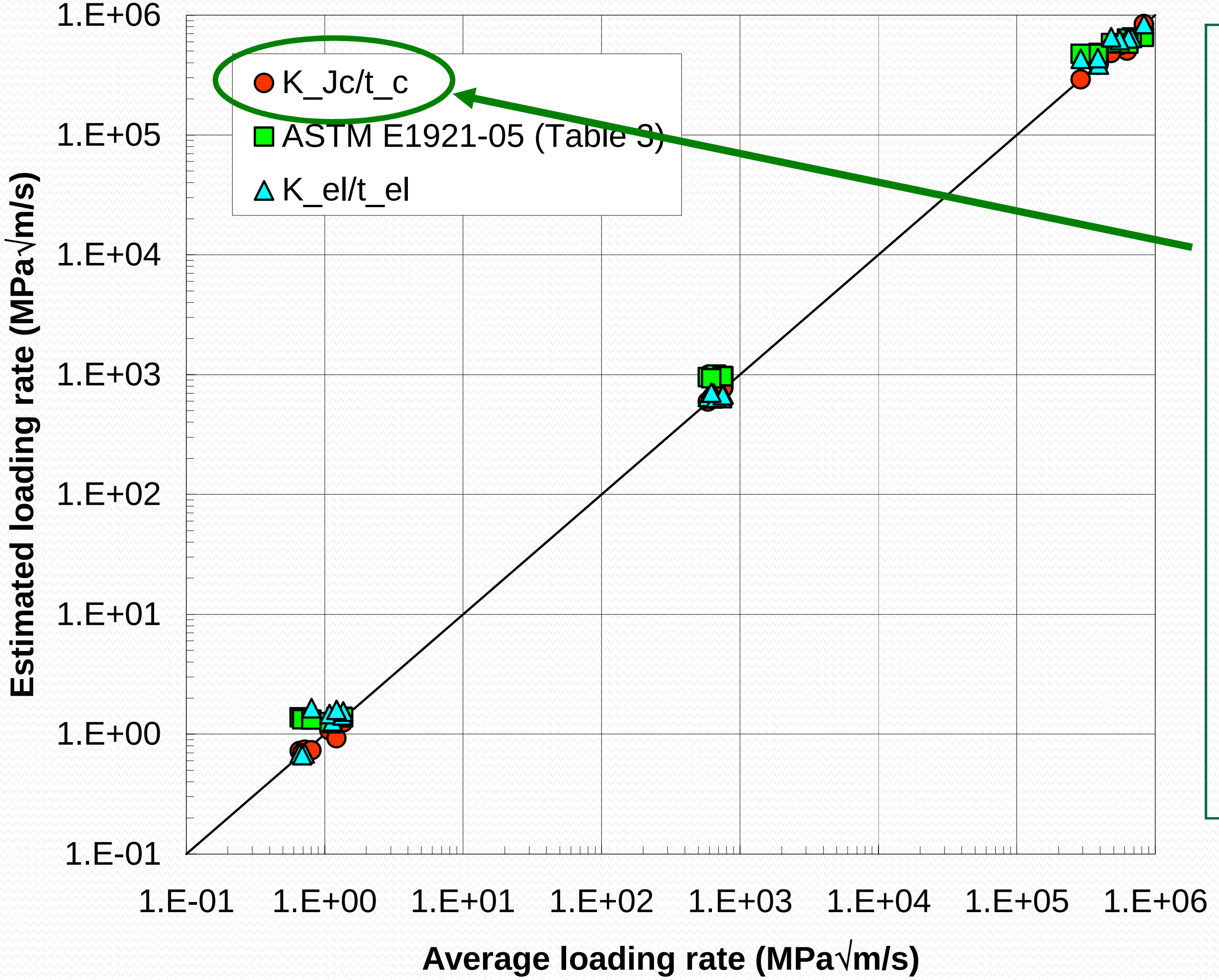


How to estimate the loading rate in a fracture toughness test

1. Average value of dK/dt calculated for each individual force/displ. data point in a test

   most straightforward but time-consuming
2. Ratio between K and time within the linear elastic region: K_{el}/t_{el}
3. Use of a table in ASTM E1921-05 which relates a/W, E and test speed to the loading rate
4. Ratio between K and time at test termination (cleavage or specimen unloading): K_c/t_c or K_f/t_f

Comparison between the different evaluation approaches



The ratio between stress intensity factor and time at test termination is recommended for practical purposes

- It's sufficiently accurate
- It requires a minimum of additional computations (only t_c determination)

Experimental determination of dynamic fracture toughness

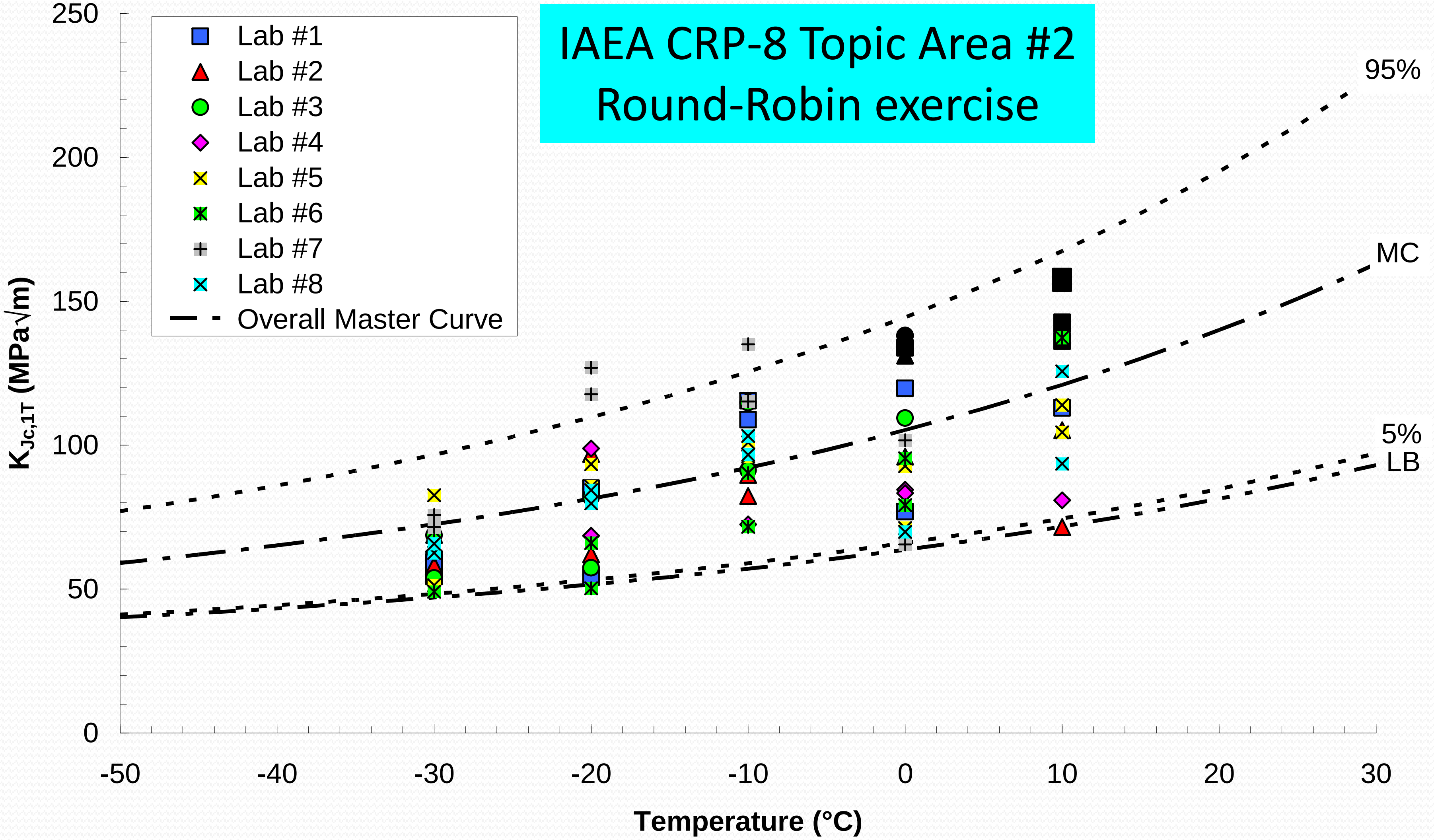
- Fully brittle behaviour -

- Quasi static range: 0.55 to 2.75 MPa√m/s (ASTM E399 and E1820) – 0.55 to 3 MPa√m/s (ISO 12135 and BS 7448:3)
- For higher loading rates:
  - force values need to be unambiguously determined
  - test time ≥ 1 ms
  - yield strength must be relevant to test rate
- ASTM E399 and E1820 explicitly exclude impact testing from free-falling or swinging masses
- *“Substantial decreases in toughness may be noted as the loading rate increases”*

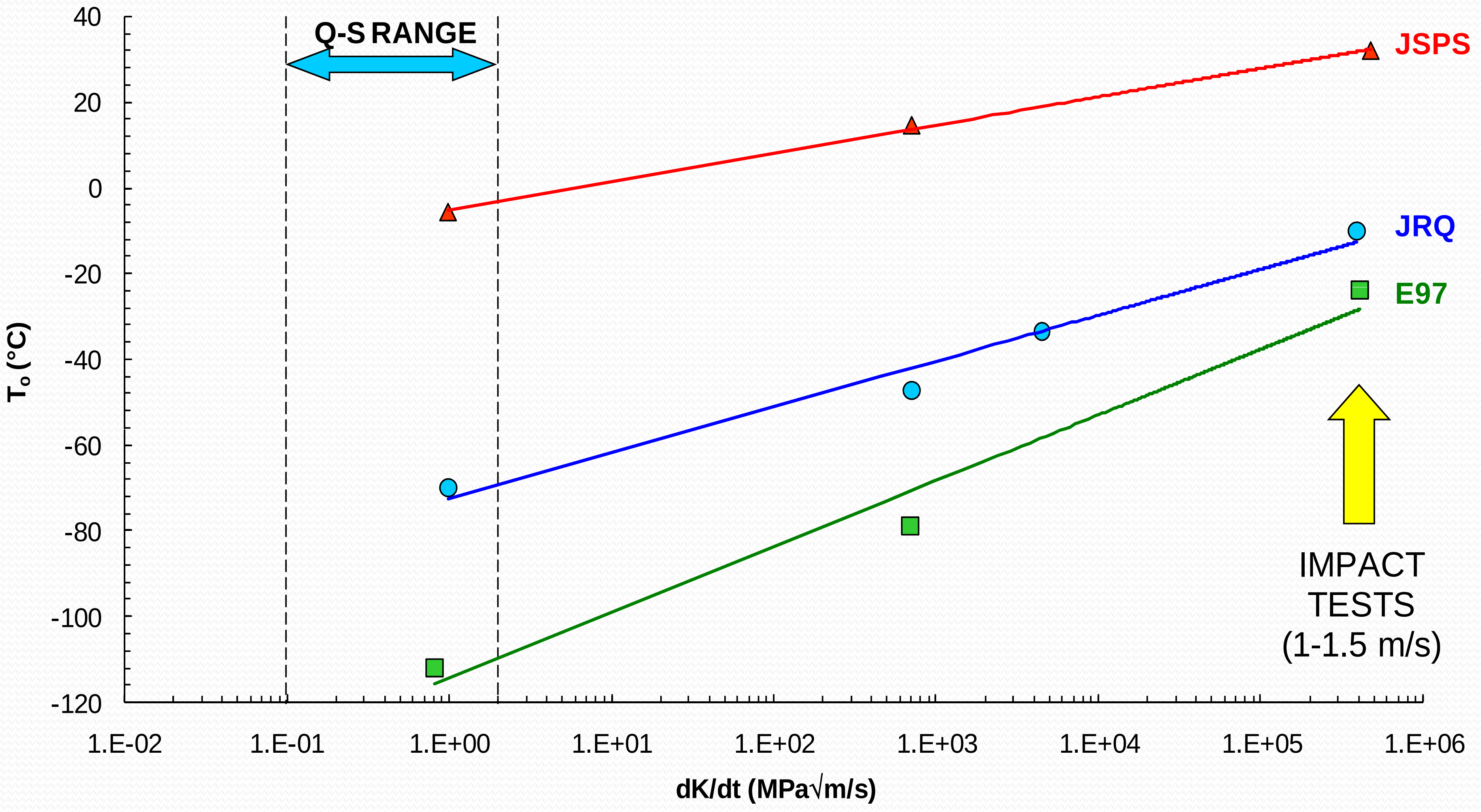
Experimental determination of dynamic fracture toughness
- Mixed brittle/ductile behaviour -

- Range allowed by ASTM E1921-09 for quasi-static evaluation: 0.1 to 2 MPa√m/s in the elastic region (influence on the reference temperature < 10 °C)
- If dK/dt < 0.1 MPa√m/s, testing is allowed if environmental effects are negligible
- Provisions for higher loading rates (dK/dt > 2 MPa√m/s) have been included in the latest version of the standard (2009), which also cover impact-tested precracked Charpy specimens)

The Master Curve is <u>fully</u> applicable to impact tests on PCC specimens



Increase of Master Curve reference temperature: different loading rate sensitivity for different steels



An empirical correlation approach between ΔT_o (or $T_{o,dyn}$) and dK/dt

$$T_{o,dyn} = \frac{T_{o,st} \cdot \Gamma}{\Gamma - \log\left(\dot{K}\right)}$$

$$\Gamma = 9.9 \cdot \exp\left[\left(\frac{T_{o,st}}{190}\right)^{1.66} + \left(\frac{\sigma_{ys\left(T_{o,st}\right)}}{722}\right)^{1.09}\right]$$

Static yield stress

(developed on 59 steels, with: $dK/dt = 10^{-1}$ to 10^{6} MPa√m/s, σ_{ys} = 200 to 1000 MPa, $T_{o,st}$ = -180 to 0 °C)

- Full reference: K. Wallin, *Effect of Strain Rate on the Fracture Toughness Reference Temperature T_o for Ferritic Steels*, in "Recent Advances on Fracture", R.K. Mahidhara, A.B. Geltmacher and K. Sadananda, eds., The Mineral, Metals & Materials Society, 1997

Experimental determination of dynamic fracture toughness
- Fully ductile behaviour -

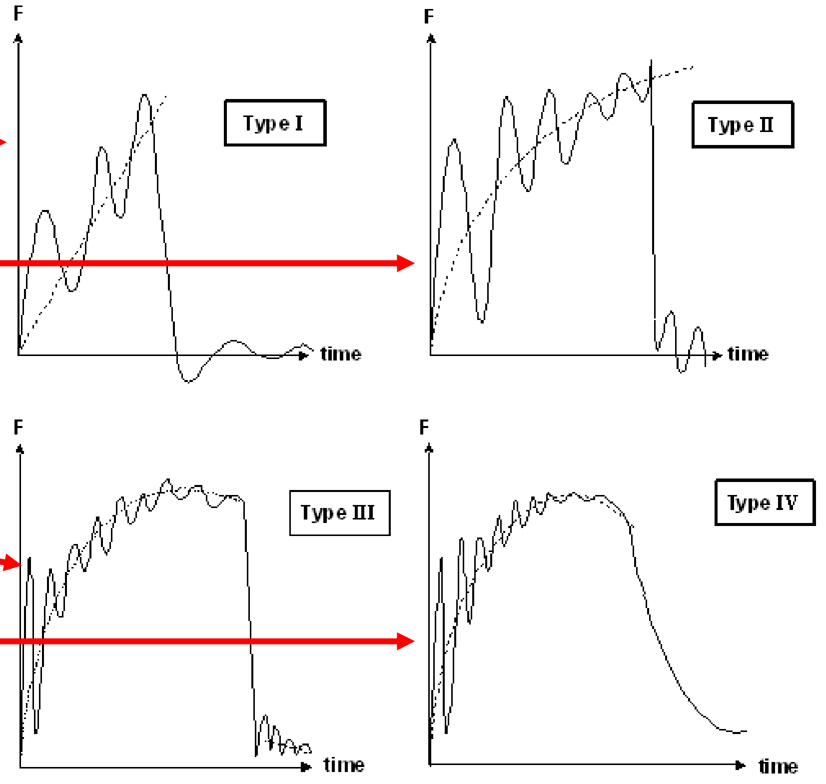
- Provisions are given in ASTM E1820 for high loading rates (Annex A14):
  - initial portion of force/displacement curve must be well defined
  - minimum test time t_w calculated from specimen stiffness and effective test mass; for test times < t_w, J-integral equations are not accurate
  - for J-R curve determination, the Normalization Data Reduction technique (Annex A15) is recommended
- *"The J-R(t) curve and* $J_{Ic}(t)$ *properties are usually elevated by higher testing rates"*

A new ISO standard and a new Annex to E1820 are in preparation to cover impact tests of PCC specimens

- Based on the latest draft of the ESIS TC5 procedure (25.4 – December 2005)
- Presently in the balloting phase both at ISO and at ASTM
- Will cover all material behaviour regimes (brittle / transition / ductile)
- Were the basis of the test procedure used for the IAEA CRP-8 round-robin exercise

Dynamic toughness from PCC specimens
Identification of material behavior

Material response/fracture behaviour	corresponding diagram type (see Fig.1)	R-curve	Characteristic Parameters (with relevant influencing parameters given in brackets)
essentially linear-elastic	I	-	K_{Id} (K_I)
elastic plastic, unstable cleavage without significant stable crack extension (Δa<0.2mm)	II	-	J_{ucd} (B, $\dot{J}$)
elastic plastic, unstable cleavage after stable crack extension (1.6mm>Δa>0.2mm)	III	-	J_{ud} (B, Δa, $\dot{J}$)
elastic plastic, unstable cleavage after gross stable crack extension (Δa>1.6 mm)	IV	J_d-R-curve δ_d-R-curve	$J_{0.2Bd}$ ($\dot{J}$) $\delta_{0.2Bd}$ ($\dot{\delta}$)
elastic plastic; no unstable crack extension	IV	J_d-R-curve δ_d-R-curve	$J_{0.2Bd}$ ($\dot{J}$) $\delta_{0.2Bd}$ ($\dot{\delta}$)



Dynamic toughness from PCC specimens
Specimens and testing machines

- Specimens
  - Allowed range of initial crack size: 0.3 ≤ a/W ≤ 0.55 (for comparison with static toughness: 0.45 ≤ a/W ≤ 0.55)
  - Side-grooving is allowed (but recommended for J-R tests)
- Testing machines
  - Various machines allowed (recommended: pendulum with variable speed; allowed: drop-weight, servo-hydraulic, special pendulum types with moving anvils)
  - Striker must conform to ISO 148-2 (tup radius: 2 mm) or ASTM E23 (tup radius: 8 mm)

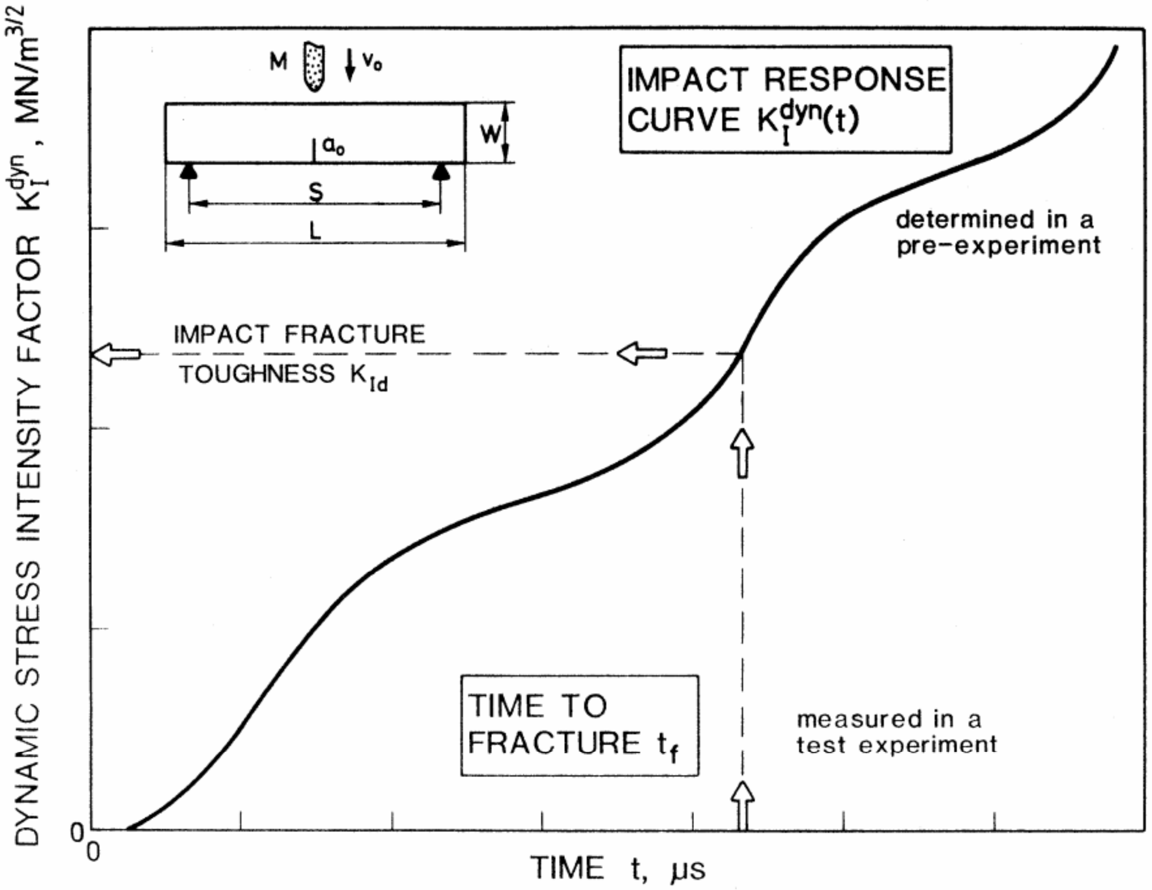
Dynamic toughness from PCC specimens
Experimental features and measurements

- *Impact velocity*: any value allowed from quasi-static up to about 5 m/s; for a Charpy pendulum, it can be reduced to approx 1 m/s
- *Time to fracture* (t_f): if $t_f < 5t$, crack initiation cannot be detected from *F*/*d* trace (independent measure is required)
- *Crack length measurements*:
  - 5-point average method (limit of non-uniform crack growth: 10%)
  - Area average method

Dynamic toughness from PCC specimens

Dynamic evaluation of fracture toughness K_{Id}

- Impact Response Curve (Kalthoff, Winkler & Böhme, DYMAT 1985)



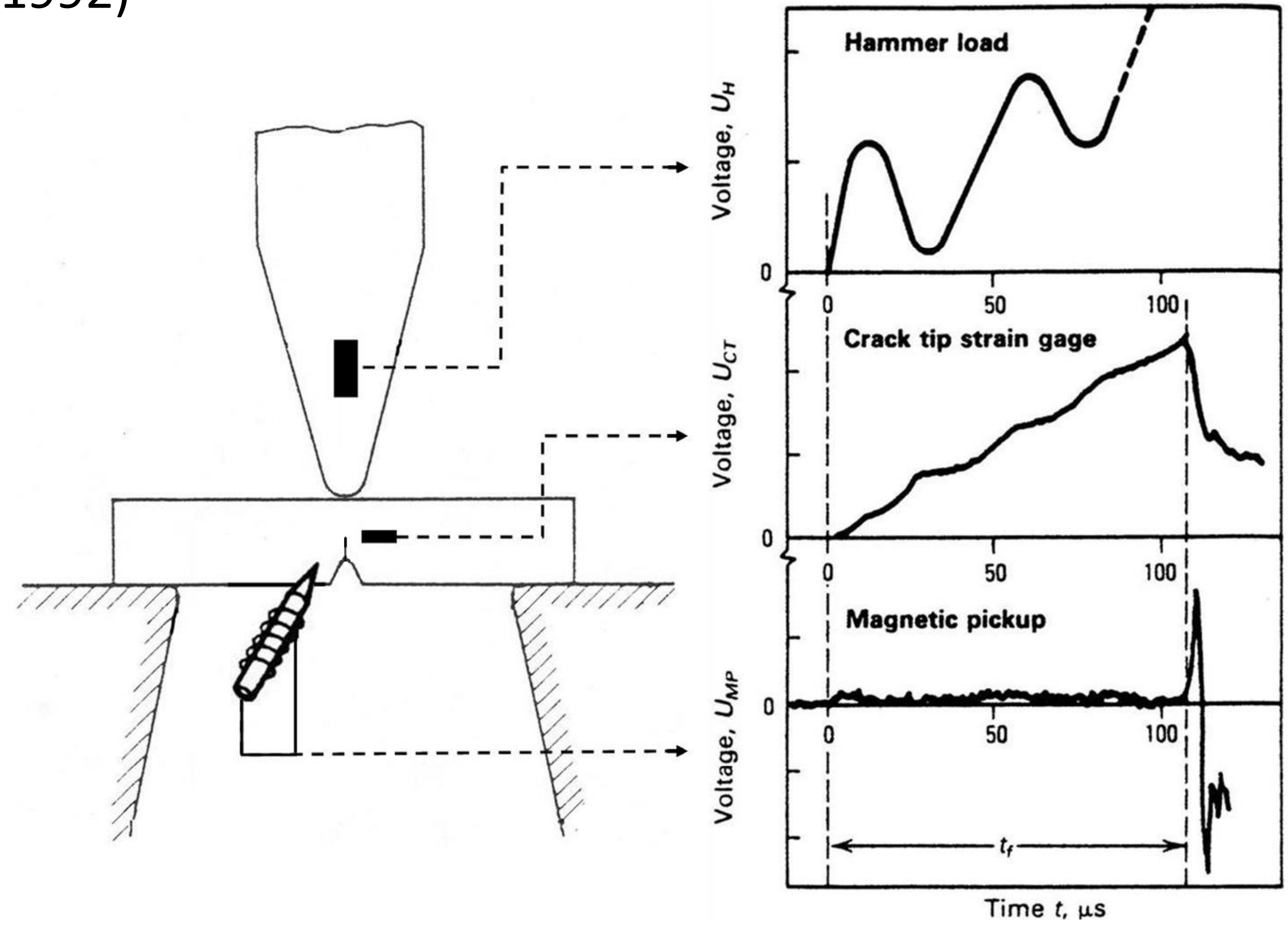
$$K_1^{dyn} = R v_o t''$$

function of machine compliance

***t''* is tabulated as a function of t_f**

Dynamic toughness from PCC specimens
Dynamic evaluation of fracture toughness K_{Id}

- <u>Crack Tip Strain Gauge Method</u> (McGillivray & Cannon, ASTM STP 1130, 1992)

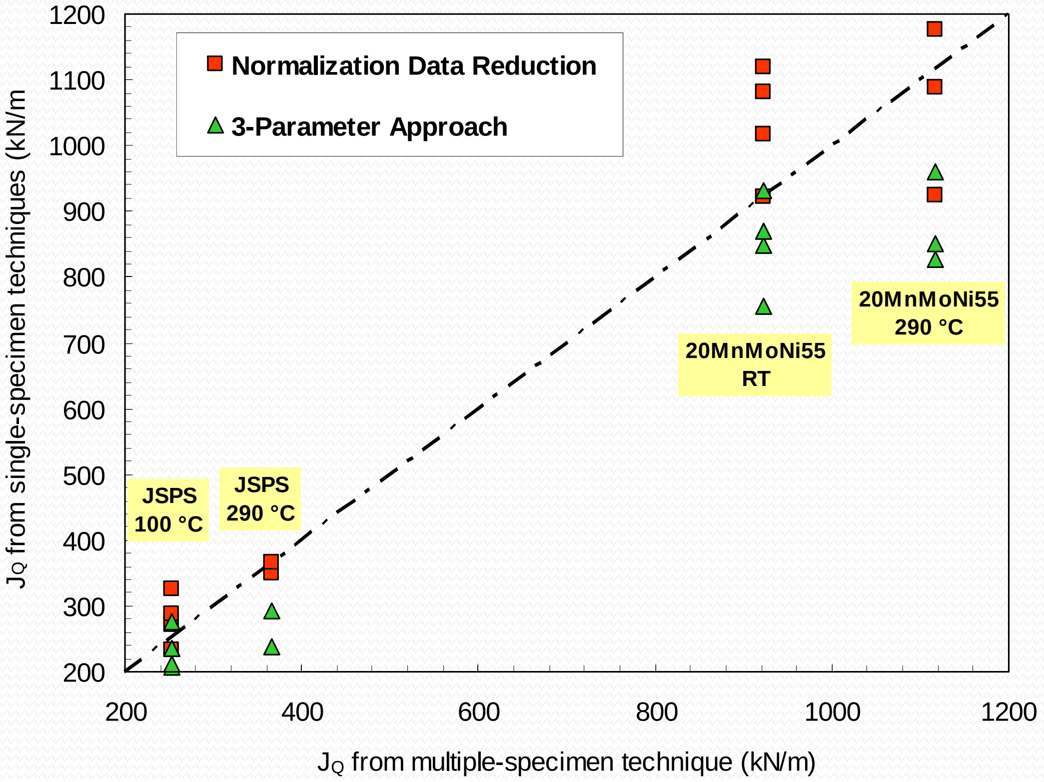


Dynamic toughness from PCC specimens Crack resistance curves by multiple-specimen methods

- Low-Blow Test
  - Impact velocity is changed to achieve variable Δa
  - Available energy sufficient for propagating the crack, but not to break the specimen fully
  - Small differences between initial velocities are neglected
- Stop Block Test
  - Striker movement is arrested before the specimen is fully broken
  - Striker arrest position is changed to achieve variable Δa
  - Not recommended for "*normal use with standard machines*" (risk of damage to the load cell)
- Cleavage R-curve Method
  - Tests are performed in the transition region, varying the test temperature in order to achieve variable Δa
  - Small differences between test temperatures are neglected

Dynamic toughness from PCC specimens Crack resistance curves by single-specimen methods

- Basic Key Curve Method (Joyce STP 791, 1983)
- Analytical 3-Parameter Approach (Schindler STP 1380, 1999)
- Normalization Data Reduction Technique (ASTM E1820)



Good agreement between multiple and single-specimen results

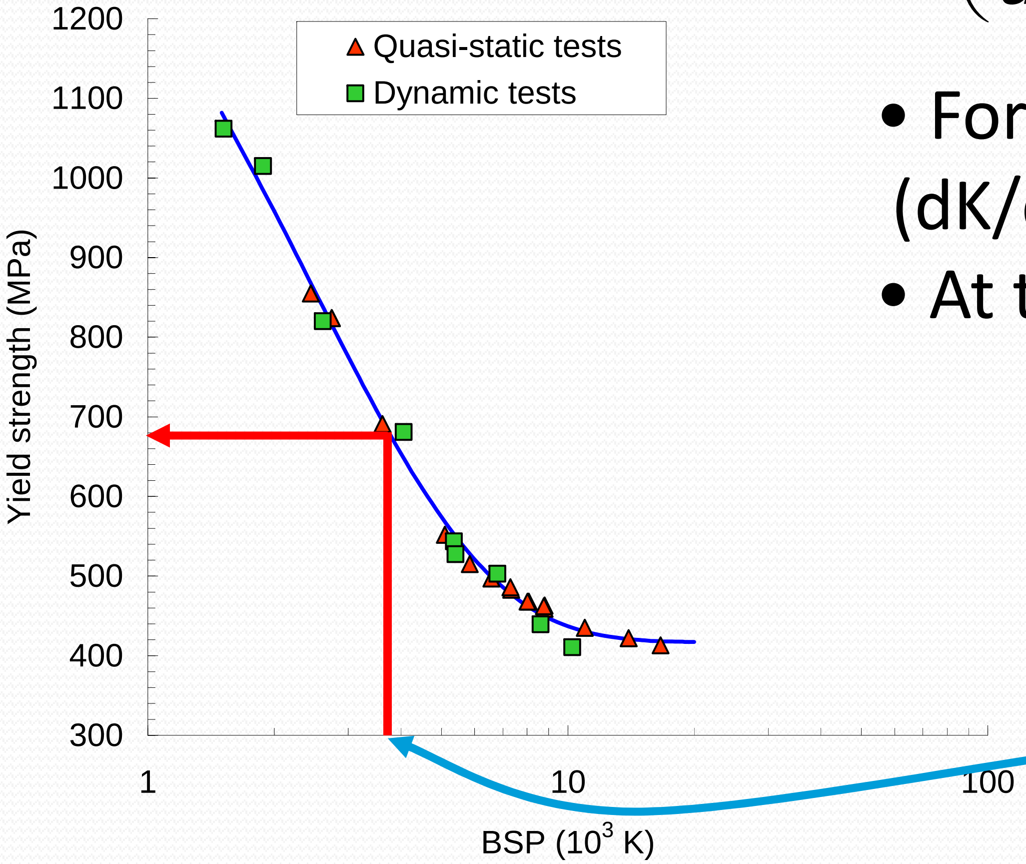
Another non-negligible issue: which tensile properties to use?

- Tensile properties (yield, ultimate, flow) at the relevant strain rates must be used
- Options available (in order of increasing accuracy):
  - use of quasi-static values is normally conservative for establishing validity criteria, but is non-conservative for establishing the upper shelf construction (blunting) line
  - estimation of dynamic values from instrumented Cv/PCC force-deflection curves (Server, Eng Fract Mech 1978)
  - high rate tensile tests (test procedure in ESIS P7-00)
- An alternative option for the yield strength: use of the Bennett-Sinclair parameter

Estimation of the yield strength using the Bennett-Sinclair parameter

$$BSP = T \cdot \ln\left(\frac{A}{d\varepsilon / dt}\right)$$

frequency factor ~ 10^8 s^{-1}



- For quasi-static loading rates: $(dK/dt)_{q\text{-}s} \Leftrightarrow (d\varepsilon/dt)_{q\text{-}s}$
- At the test loading rate:

$$\left(\frac{d\varepsilon}{dt}\right)_{test} = \left(\frac{dK}{dt}\right)_{test} \frac{(d\varepsilon / dt)_{q-s}}{(dK / dt)_{q-s}}$$

$$\Downarrow$$

BSP (T_{test}, $(d\varepsilon/dt)_{test}$)

The practical importance of reducing impact velocity

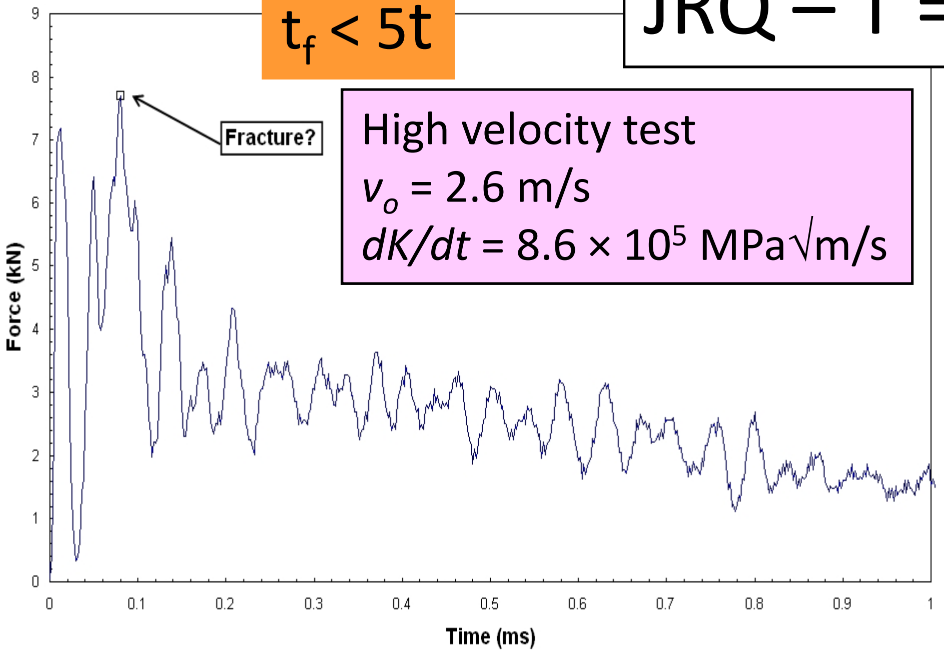
- Reduced impact velocity

$E_p = 10 \div 20$ J $v_o = 0.8 \div 1.5$ m/s

(minimization of inertial oscillations)

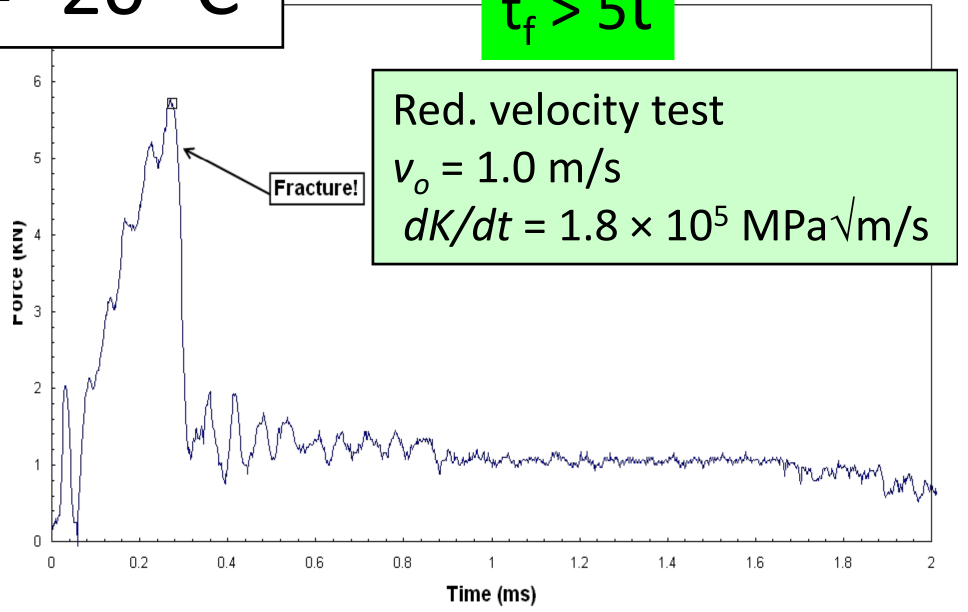
JRQ – T = -20 °C

$t_f < 5t$



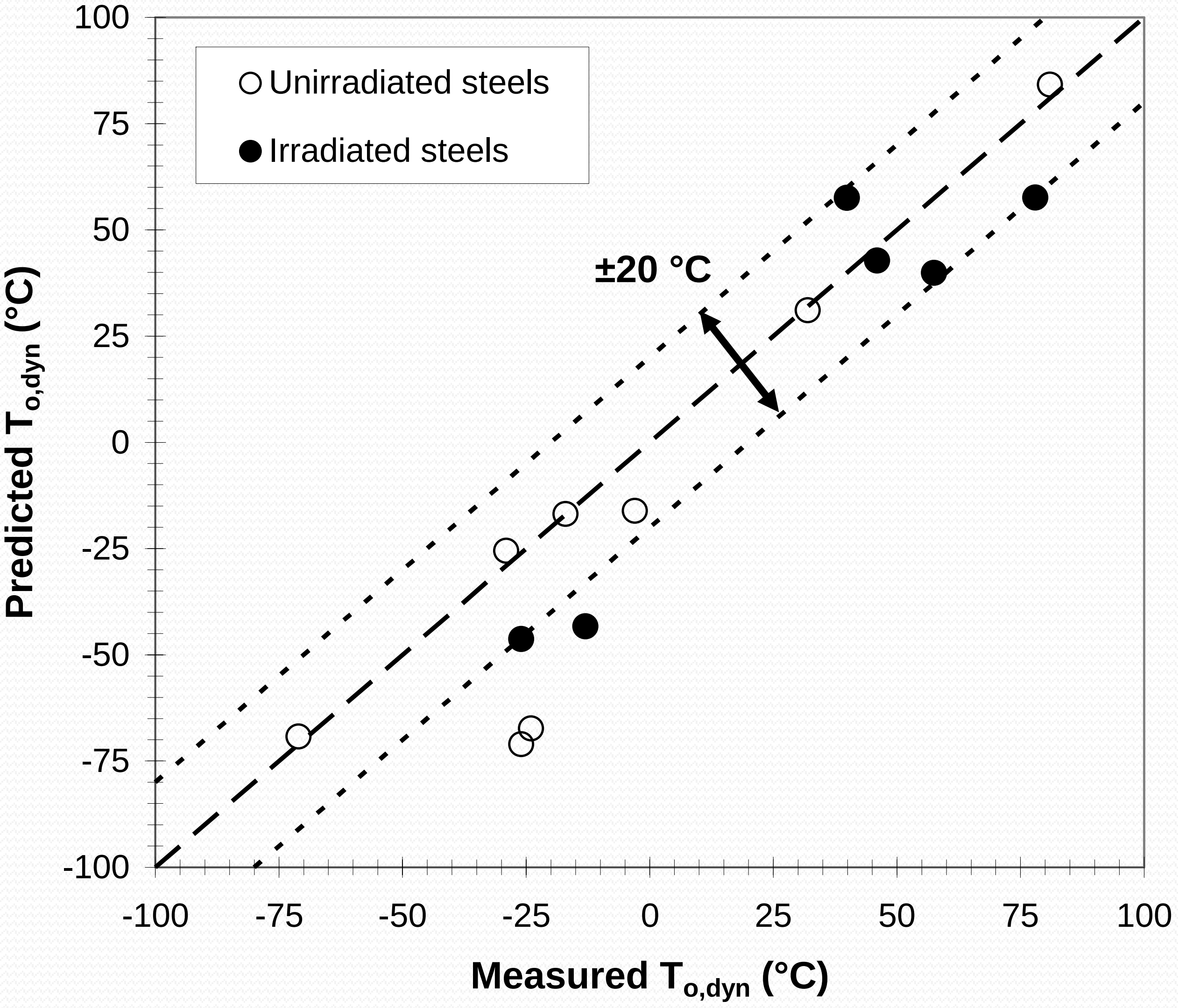
High velocity test
v_o = 2.6 m/s
$dK/dt = 8.6 \times 10^5$ MPa√m/s

$t_f > 5t$



Red. velocity test
v_o = 1.0 m/s
$dK/dt = 1.8 \times 10^5$ MPa√m/s

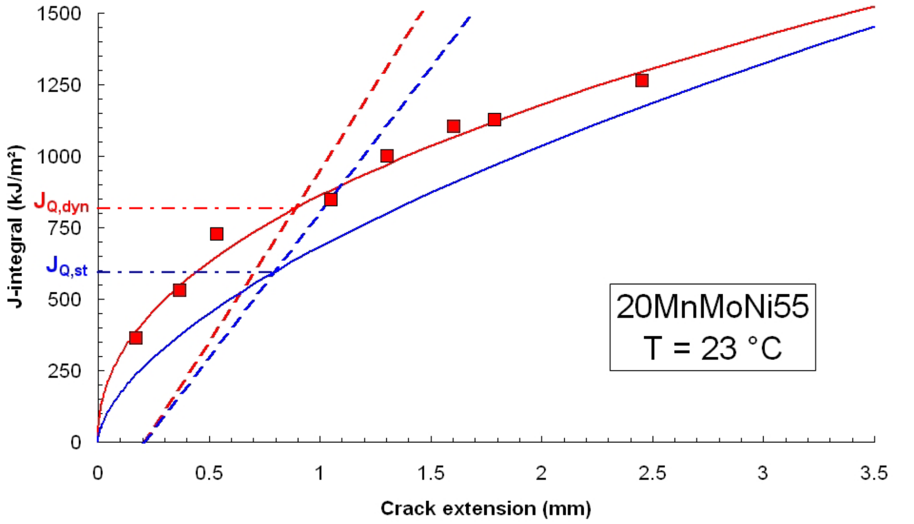
Verification of Wallin's empirical model

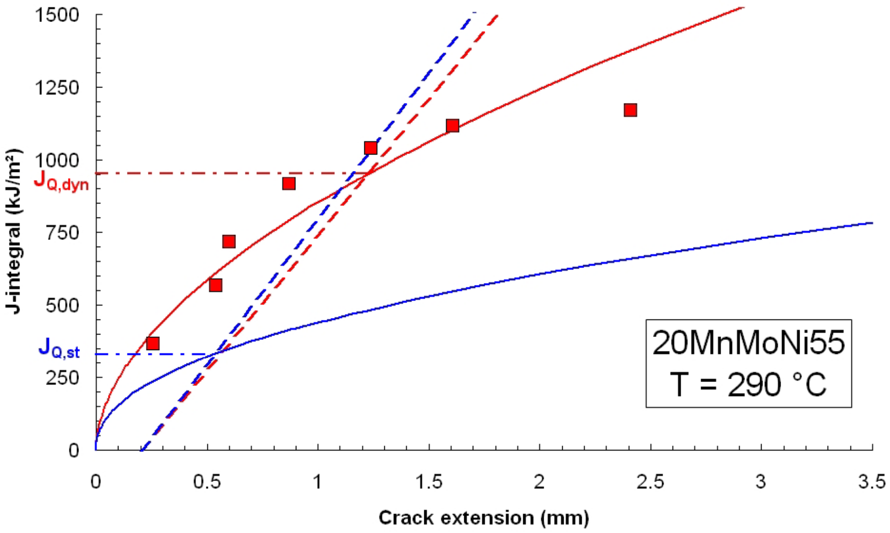


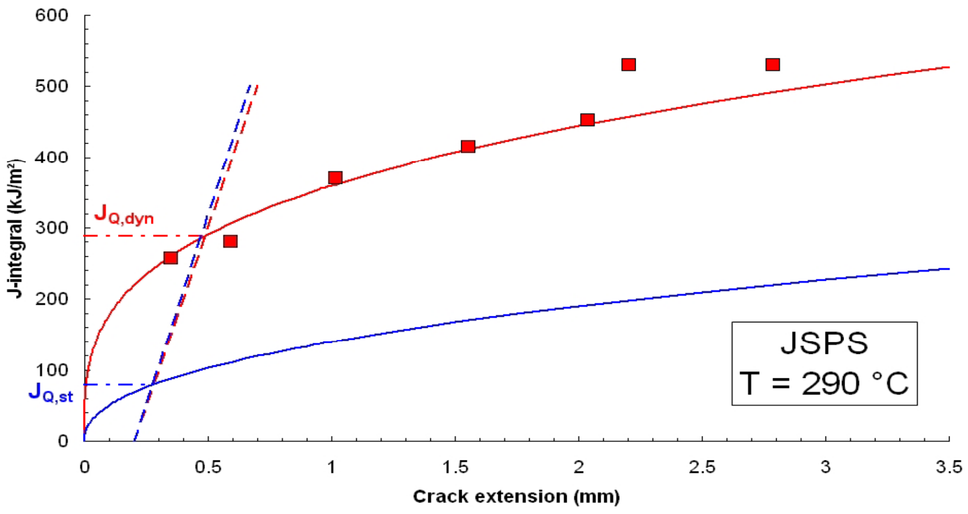
Main application in ASTM E1921-09

Selection of the test temperature for dynamic toughness tests (similar to the correlations with T_{28J}/T_{41J} for quasi-static tests)

Effect of loading rate on ductile resistance curves (red: dynamic / blue: static)







Significant increase of toughness (critical value and crack resistance), particularly at high temperatures