Joint ICTP/IAEA Workshop on Irradiation-induced Embrittlement of Pressure Vessel Steels

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Influence of loading rate on fracture mechanics properties

Enrico Lucon

*Italy
Influence of Loading Rate on Fracture Mechanics Properties

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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?

- **Lower shelf** (*fully brittle behavior*): toughness decreases with loading rate $\Rightarrow K_{ld} < K_{lc}$

- **Ductile-to-brittle transition regime** (*mixed brittle/ductile behavior*): transition/reference temperature increases with loading rate $\Rightarrow T_{o,dyn} > T_{o,st}$

- **Upper shelf** (*fully ductile behavior*): toughness (initiation/propagation) increases with loading rate $\Rightarrow J_{ld} > J_{lc}$
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.

Fracture stress (weakly dependent on temperature or loading rate).

Conditions for cleavage:

Temperature shift ($\Delta T$)

Yield increase ($\Delta \sigma_y$)

Transition temperature shift (embrittlement)

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

20MnMoNi55

$T = 290 \, ^\circ C$
Overall effect of loading rate increase on steel toughness
How to estimate the loading rate in a fracture toughness test

1. Average value of $\frac{dK}{dt}$ 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: $\frac{K_{el}}{t_{el}}$

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): $\frac{K_c}{t_c}$ or $\frac{K_f}{t_f}$
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 fully applicable to impact tests on PCC specimens

IAEA CRP-8 Topic Area #2
Round-Robin exercise
Increase of Master Curve reference temperature: different loading rate sensitivity for different steels

**Graph Details:**
- **Axes:**
  - Y-axis: $T_0$ (°C)
  - X-axis: $dK/dt$ (MPa√m/s)

**Legend:**
- JSPS
- JRQ
- E97

**Impact Tests:**
- 1-1.5 m/s

**Q-S RANGE**
- indicated on the graph with an arrow.
An empirical correlation approach between $\Delta T_o$ (or $T_{o,dyn}$) and $dK/dt$

\[ T_{o,dyn} = \frac{T_{o,\text{st}} \cdot \Gamma}{\Gamma \cdot \log(K)} \]

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

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

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 $J_{lc}(t)$ 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**

<table>
<thead>
<tr>
<th>Material response/fracture behaviour</th>
<th>corresponding diagram type (see Fig.1)</th>
<th>R-curve</th>
<th>Characteristic Parameters (with relevant influencing parameters given in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>essentially linear-elastic</td>
<td>I</td>
<td>-</td>
<td>( K_d ) (( K_i ))</td>
</tr>
<tr>
<td>elastic plastic, unstable cleavage without significant stable crack extension (( \Delta a \approx 0.2 ) mm)</td>
<td>II</td>
<td>-</td>
<td>( J_{ud} ) (( B, J ))</td>
</tr>
<tr>
<td>elastic plastic, unstable cleavage after stable crack extension (1.6 mm &gt; ( \Delta a &gt; 0.2 ) mm)</td>
<td>III</td>
<td>-</td>
<td>( J_{ud} ) (( B, \Delta a, J ))</td>
</tr>
</tbody>
</table>
| elastic plastic, unstable cleavage after gross stable crack extension (\( \Delta a > 1.6 \) mm) | IV                                   | \( J_d \)-R-curve \( \delta_d \)-R-curve | \( J_{0.25a} \) (\( J \))  
\( \delta_{0.25a} \) (\( \delta \)) |
| elastic plastic, no unstable crack extension | IV                                   | \( J_d \)-R-curve \( \delta_d \)-R-curve | \( J_{0.25a} \) (\( J \))  
\( \delta_{0.25a} \) (\( \delta \)) |
Dynamic toughness from PCC specimens

Specimens

- Allowed range of initial crack size: $0.3 \leq a/W \leq 0.55$ (for comparison with static toughness: $0.45 \leq a/W \leq 0.55$)
- 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 $K_{1d}$

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

$$K_{1d}^{\text{dyn}} = R v_o t''$$

function of machine compliance

$t''$ is tabulated as a function of $t_f$
Dynamic toughness from PCC specimens

*Dynamic evaluation of fracture toughness $K_{ld}$*

- **Crack Tip Strain Gauge Method** (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 $\Delta a$
  - 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 $\Delta a$
  - 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 $\Delta a$
  - 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 \textit{conservative} for establishing validity criteria, but is \textit{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

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

- For quasi-static loading rates:
  \[(dK/dt)_q-s \leftrightarrow (d\varepsilon / dt)_q-s\]
- At the test loading rate:
  \[\left( \frac{d\varepsilon}{dt} \right)_\text{test} = \left( \frac{dK}{dt} \right)_\text{test} \frac{(d\varepsilon / dt)_{q-s}}{(dK / dt)_{q-s}}\]

\[BSP (T_\text{test}, (d\varepsilon / dt)_\text{test})\]
The practical importance of reducing impact velocity

- Reduced impact velocity

\[ E_p = 10 \div 20 \text{ J} \quad v_o = 0.8 \div 1.5 \text{ m/s} \]

(minimization of inertial oscillations)

\[ t_f < 5t \quad \text{JRQ} - T = -20 \ ^\circ C \quad t_f > 5t \]

High velocity test
\[ v_o = 2.6 \text{ m/s} \quad \frac{dK}{dt} = 8.6 \times 10^5 \text{ MPa} \sqrt{\text{m/s}} \]

Red. velocity test
\[ v_o = 1.0 \text{ m/s} \quad \frac{dK}{dt} = 1.8 \times 10^5 \text{ MPa} \sqrt{\text{m/s}} \]
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