Considering the Statistical Distribution of Dynamic Fracture Toughness Data and the Actual Loading Rate at Fracture Initiation when applying ASTM E1921 at Elevated Loading Rates

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Outline

- Introduction
- Loading rate definition in existing standards
- Proposal of a new definition of the loading rate
- Test equipment for fracture mechanic tests at high loading rates
- Discussion of results obtained from tests at high loading rate
- Analysis of local stress history
- Multi-Temperature results at $10^5$ MPa$\sqrt{m}$ s$^{-1}$, 1T C(T)
- Conclusion
Commonly different parameters are used for characterizing the loading rate of linear-elastic and elastic-plastic fracture mechanics test. For linear-elastic tests $\frac{dK}{dt}$ can be kept approximately constant during the test, for elastic-plastic tests $\frac{dJ}{dt}$ is constant after an initial acceleration during the linear-elastic part of the test.

- $\frac{dK}{dt}$ is the loading rate parameter for linear-elastic tests.
- $\frac{dJ}{dt}$ is the loading rate parameter for elastic-plastic tests.

For the use of a Master Curve evaluation according to ASTM E1921 in the transition range of fracture toughness, results from both types of tests are used: fracture toughness $K$ for linear-elastic tests and formally calculated values $K_J$ from $J$ for elastic-plastic tests. The open question regards the relevant loading rate, especially if different test series are compared, e.g. one test series with unstable crack initiation during linear-elastic loading and the other one with similar $K_J$-values calculated formally from $J$-values, being elastic-plastic due to smaller dimensions.
Introduction

- Results of a research project investigating the correlation of dynamic crack initiation and crack arrest, Böhme. (2012), that was funded by the German government, show differences of up to 30 K in $T_{0,X}$ obtained from linear-elastic test series and $T_{0,X}$ obtained from elastic-plastic test series with comparable $dK/dt$.

- Dynamic fracture mechanics testing is specified in annexes of the standards ASTM E399 and E1820 and also in BS7448-3. In these standards fracture mechanics values $J$ and $K$ are determined basically the same way as for quasi-static tests.

- $K = \frac{F}{\sqrt{B \times B_N \times W}} f(a/w)$

and

- $J = J_{el} + \frac{\eta_{pl} \times A_{pl}}{B_N \times b_0}$
Loading rate definition in existing standards

- ASTM E 399 A10 (special requirements for rapid force, plane-strain fracture toughness $K_{IC}(t)$ testing)
  
  $\frac{dK}{dt} = K_Q/t$

- BS 7448 part 3 (3 MPa\(\sqrt{m/s < \frac{dK}{dt}} < 3\times10^3 \text{ MPa}\sqrt{m/s}$)
  
  In BS 7448-3 two definitions for the loading rate are given:
  
  $\frac{dK}{dt}$ during the initial elastic loading of the specimen and the rate of change of the plastic component of the J integral $\frac{dJ_p}{dt}$, determined using the time interval for plastic deformation of the test specimen.

- In ASTM E 1820 Annex 14 (rapid-load J-integral fracture toughness testing), also two different loading rate quantities are defined:

  - $(\frac{dJ}{dt})_I$ measured before $J_Q(t)$, and $(\frac{dJ}{dt})_T$ measured after $J_Q(t)$, where $J_Q(t)$ is the provisional, rate dependent J Integral at the onset of stable crack extension. $(\frac{dJ}{dt})_I$ is defined by using a linear regression analysis between 0.5 $J_Q(t)$ and $J_Q(t)$, even if the increase is quadratic over time (Figure 1).
  
  - The second loading rate is defined as the slope of the J versus time data beyond maximum force.
Loading rate definition in existing standards

ASTM E1820 (linear fit)

\[
\begin{align*}
(dJ/dt)_I &= 2.8 \times 10^5 \text{ N mm}^{-1} \text{ s}^{-1} \\
(dK/dt) &= 5.1 \times 10^5 \text{ MPam}^{0.5} \text{ s}^{-1}
\end{align*}
\]
These different definitions for the different parts of a fracture mechanics test at elevated loading rate are both useful for characterizing the loading rates of the tests. Only if results from both, linear-elastic tests and elastic-plastic tests are assessed together to describe the influence of the loading rate on cleavage fracture toughness for a material a unified definition of the loading rate for both types of tests is needed. This applies especially to the Master Curve evaluation according to ASTM E1921.

Since the J-integral correlates quadratic with K, the question arises during application of ASTM E1921 at high loading rates, if for the elastic-plastic range a quadratic increase of the J-integral leads to a loading rate comparable to linear-elastic tests.

However, usual testing conditions with constant displacement rate result in a linear increase of the J-integral over time in the plastic regime after the initial acceleration during the linear-elastic part of the test.
We analyze the correlation of the change over time of $K$ and the change over time of $J$ in the case of a linear-elastic fracture mechanics test for constant $dK/dt$:

- $J = \frac{K^2(1-\nu^2)}{E}$ \hspace{1cm} (1)
- $\frac{dJ}{dt} = \frac{2K \times dK/dt \times (1-\nu^2)}{E}$ \hspace{1cm} (2)
- $\frac{d^2J}{dt^2} = \frac{2(1-\nu^2)}{E} \times \left(\frac{dK}{dt}\right)^2$ \hspace{1cm} (3) terms with $\frac{d^2K}{dt^2}$ vanish because $\frac{dK}{dt} = \text{constant}$

solving for $dK/dt$ leads to:

- $\frac{dK}{dt} = \sqrt{\frac{E}{2(1-\nu^2)}} \times \frac{d^2J}{dt^2}$ \hspace{1cm} (4)

- $K = \text{stress intensity factor (time series)}$
- $E = \text{Youngs modulus}$
- $J = \text{J-Integral (time series)}$
- $\nu = \text{Poisson’s ratio}$
- $dK/dt = \text{loading rate}$

Proposal: Transfer of this correlation also to the elastic-plastic regime.
Servo-hydraulic Testing Device

Servo-hydraulic testing machine
(VHS 100/20 Schenck/Instron)

- \( F_{\text{max}} = 100 \text{ kN}, \)
  \( v_{\text{max}} = 20 \text{ m/s} \)

- This machine incorporates large hydraulic accumulators (2x 280 l), high flow rate servovalves (6400 l/min) and a special slack adapter such that almost constant displacement rates during a complete test could be achieved.

- The slack adapter minimizes the mass to be accelerated and hence reduces oscillations.

- The computer controlled valves (6400 l/min) allow the load time characteristics to be optimized for any particular test condition or material.
At high loading rates the only acceptable force measurement technique is the use of strain gauges on parts of the specimen, which remain elastic during the test.

In previous investigations positions on the upper (fixed) part and lower (moving) part of the specimen at which the strain behaves accordingly proportional to force were identified by means of numerical simulation.
At loading rates up to $2 \times 10^5$ MPa$\sqrt{m \ s^{-1}}$, the time of the start of unstable crack propagation can be determined from the load drop measured using the force strain gauges. This instant of time correlates well with that indicated by the crack tip strain gauges.
The specimens were extracted from the middle sector of the RPV with crack tip between 2/3 and ¾ of the thickness.
Mastercurve evaluation according to ASTM E 1921

Force vs. Crack Opening Displacement and Mastercurve according to ASTM E1921 for the test series at -20°C, 2x10^5 MPa/m s⁻¹

Material: 22 NiMoCr 3 7 (similar to A 508 Cl.2)
Specimen type: 1T C(T) (Materials Testing Institute University of Stuttgart)
Test device: High rate servo-hydraulic

\[ K_{JC,50\%} = 30 + 70 \exp \left[ 0.019 \left( T - T_{0,\text{quasi-static}} \right) \right], \quad T_{0,\text{quasi-static}} = -68°C \]

\[ K_{JC,d,50\%} = 30 + 70 \exp \left[ 0.019 \left( T - T_{0,5} \right) \right], \quad T_{0,5} = +15°C \]
Mastercurve evaluation according to ASTM E 1921

Results from pendulum tests with SEB 10/10.
Tests performed at Fraunhofer Institute for Mechanics of Materials, IWM, Freiburg.

Force vs. Displacement and Mastercurve according to ASTM E1921 for the test series at -20°C, 3x10⁵ MPa√m s⁻¹

$T_{0.5}=-7°C$
Analysis of a pendulum test with a SE(B) 10/10 specimen

Test performed at Fraunhofer Institute for Mechanics of Materials, IWM, Freiburg.

Force-displacement curve of a pendulum test with a SE(B) 10/10 specimen at 1m/s, resulting in $\frac{dK}{dt} = 3 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}}$ (Fraunhofer Institute for Mechanics of Materials, IWM, Freiburg)

First derivative of $J(t)$ and $K_I(t)$ during test time and $(dJ/dt)_I$ according ASTM E1820, A14
Analysis of a pendulum test with a SE(B) 10/10 specimen

Above $J=58 \text{ N/mm}$ ($K_{J}=116 \text{ MPa} \sqrt{\text{m}}$, $K_{J}(1T)=96 \text{ MPa} \sqrt{\text{m}}$)

dK/dt calculated with the proposed definition declines below $10^5 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1}$, while the rate of $K_{J}$ calculated after conversion from $J$ is near to $3 \times 10^5 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1}$ for the entire test.

$dK_{J}/dt$ compared to

$$\frac{dK}{dt} = \sqrt{\frac{E}{2(1-\nu^2)}} \times \frac{d^2 J}{dt^2}$$
Result of an analysis of the quasi-static loading of a 1T C(T) specimen.

For linear elastic tests the major principal stress in the region, where the unstable crack starts, shows a sharp increase with crack opening displacement (COD). If plastic deformation starts to be a significant part of the macroscopic specimen behavior, the incline of the major principal stress with COD becomes more and more gentle, especially if the maximum moves towards the ligament with increasing distance from the fatigue pre-crack.
- The time course of this major principal stress plays a tangential role for the behavior of the material as long as the test is quasi-static and there is no or only small sensitivity to the loading rate.

- This changes significantly for higher loading rates. Dynamic fracture tests are generally performed using a constant displacement rate, thus the COD is proportional to time.

- In case of dynamic tests we can transfer these observations of the increase of the stress normal to the fracture plane with COD to the stress rate relating to time. This view on the local stress rate near the unstable crack initiation supports the conception that the loading rate is decreasing, if the test ceases to be globally linear-elastic.
Following this proposal the result of tests should not be included in the
determination of $T_{0.5}$ if the loading rate is too low at cleavage initiation.

This is the case for 6 out of 32 tests of the
test series with 1 m/s displacement rate
using the pendulum machine and has a
strong effect on the determined value for
the reference temperature $T_{0.5}$.

This can be seen as a population of data
above 100 MPa$\sqrt{\text{m}}$. If we censored the
$K_{Jcd}(1\text{T})$-values higher than 96 MPa$\sqrt{\text{m}}$, as
it would be done if the values were higher
than $K_{Jclimit}$, $T_{0.5}$ would be evaluated to +2°C
instead of -7°C, calculated according to the
current edition of ASTM E1921.

Tests performed at Fraunhofer Institute for
Mechanics of Materials, IWM, Freiburg.
Multi-Temperature results at $10^5$ MPa$\sqrt{\text{m}}$ s$^{-1}$, 1T C(T)

Force vs. Crack Opening Displacement and Mastercurve according to ASTM E1921 for the first test series of the current project at 20°C, 7x10$^5$ MPa$\sqrt{\text{m}}$ s$^{-1}$

This test series seems to verify the $T_{0.5}=+15^\circ$C determined in the previous project at -20°C, 2x10$^5$ MPa$\sqrt{\text{m}}$ s$^{-1}$
Mastercurve evaluation assuming Log-Normal distribution as it is done for crack arrest using ASTM E1221. The lower bound shows better agreement with the $K_{IR}$ curve than the lower bound according to ASTM E1921.
Multi-Temperature results at $10^5$ MPa$\sqrt{m}$ s$^{-1}$, 1T C(T)

Fracture Toughness $K_{\text{id}}$ [MPa$\sqrt{m}$] vs. Temperature $T$ [°C]

- $K_{J_{c\_50\%}}$
- $K_{J_{c\_5\%}}$
- $2 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$
- $7 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$
- $T_{0.5} = +3$ °C
- $1T$ C(T) $dK/dt = 2-7 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$

15th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics, May 20-22, 2015, Anaheim, CA
Multi-Temperature results at $10^5 \text{ MPa} \sqrt{\text{m} \text{ s}^{-1}}$, 1T C(T)

Fracture Toughness $K_{\text{id}}$ [MPa$\sqrt{\text{m}}$]

Temperature $T$ [°C]

- $T_{0.5} = -5$ °C
- $1T \text{ C(T)} \frac{dK}{dt} = 2 \times 10^5 \text{ MPa} \sqrt{\text{m} \text{ s}^{-1}}$

$K_{\text{Jc}, \text{d}_50\%}$
$K_{\text{Jc}, 5\%}$
$K_{\text{Jc}, \text{d}_5\%}$
$K_{\text{IR}}$
Multi-Temperature results at $10^5$ MPa$\sqrt{m}$ s$^{-1}$, 1T C(T)

Fracture Toughness $K_{f}$ [MPa$\sqrt{m}$]

Temperature $T$ [°C]

$K_{Jc, d = 50\%}$

$K_{Jc, 5\%}$

$2 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$

$7 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$

$T_{0.5} = +17$ °C

$1T$ C(T) $dK/dt = 7 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$

15th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics, May 20-22, 2015, Anaheim, CA
Multi-Temperature results at $10^5 \text{ MPa} \sqrt{\text{m s}^{-1}}$, 1T C(T)
- We got different results for
  \[ \frac{dK}{dt} = 2 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}} (X = \log (\frac{dK}{dt}) = 5.3) \]
  and \( \frac{dK}{dt} = 7 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}} (X = \log (\frac{dK}{dt}) = 5.8) \)
  Because of this significant difference we use two digits for \( X \):
  \( T_{0.53} \) and \( T_{0.58} \)

- Mastercurve: \( K_{JC,d_{50\%}} = 30 + 70 \exp [ p(T - T_{0,X}) ] \)

  Obviously the shape of the Mastercurve used for the evaluation of quasistatic tests
  according to ASTM E1921, is not appropriate for these dynamic test results.
  We try the proposal of Schindler:

  Quasi-static Mastercurve: \( p = 0.019 \)
  - \( K_{JC,d_{50\%}} = 30 + 70 \exp [ 0.019 (T - T_{0,X}) ] \)

  Proposal Schindler: using a rate dependent, with a value for \( p \) up to 0.045
  We make a first attempt using \( p = 0.03 \)
  - \( K_{JC,d_{50\%}} = 30 + 70 \exp [ 0.03 (T - T_{0,X}) ] \)
Multi-Temperature results at $10^5 \text{ MPa} \sqrt{\text{m} \text{ s}^{-1}}$, $1T \ C(T)$

Fracture Toughness $K_{\text{id}}$ [MPa$\sqrt{\text{m}}$] vs. Temperature $T$ [°C]

- $K_{\text{Jc, d}_50\%}$
- $K_{\text{Jc}_5\%}$
- $K_{\text{Jc}_5\%}$
- $K_{\text{IR}}$

$T_{0.53} = 0$ °C, $p=0.03$

$1T \ C(T) \ \text{d}K/\text{d}t = 2 \times 10^5 \text{ MPa} \sqrt{\text{m} \text{ s}^{-1}}$
Multi-Temperature results at $10^5$ MPa$\sqrt{m}$ s$^{-1}$, 1T C(T)

Fracture Toughness $K_{id}$ [MPa$\sqrt{m}$]

Temperature $T$ [°C]

$K_{Jc, 50\%}$

$K_{Jc, 5\%}$

$K_{Jc, d, 50\%}$

$K_{IR}$

$T_{0.58} = +17$ °C

$1T$ C(T) $dK/dt = 7 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$
Multi-Temperature results at $10^5$ MPa√m s$^{-1}$, 1T C(T)

Fracture Toughness $K_{id}$ [MPa√m]

Temperature $T$ [°C]

$K_{Jc,5\%}$

$K_{Jc,d,5\%}$

$K_{IR}$

$T_{0.58} = +14$ °C, $p=0.03$

$1T C(T)$ $\frac{dK}{dt} = 7 \times 10^5$ MPa√m s$^{-1}$
For the test series at $dK/dt = 2 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}}$ the Mastercurve with $p=0.03$ seems to fit very well. For the test series at $dK/dt = 7 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}}$ the Mastercurve is too low at $-20 \, ^\circ\text{C}$.

This shows, that the steeper Mastercurve with $p=0.03$ is not valid over the whole transition range and a narrower validity range than $\pm 50 \, ^\circ\text{K}$ has to be used if this modification of the Mastercurve for high rate loading is applied.

With the currently limited number of tests at $dK/dt = 2 \times 10^5 \text{ MPa} \sqrt{\text{m s}^{-1}}$ and $20 \, ^\circ\text{C}$ the proposed censoring method is not applicable.

More tests have to be performed to enhance the statistical significance of the analysis.

If the test temperature is very near to $T_{0,x}$ (less than $10 \, ^\circ\text{K}$) the influence of the used exponential factor $p$ of the Mastercurve has clearly no significant influence on the determined $T_{0,x}$.
A new definition of the loading rate is proposed for the transition range of fracture toughness. This can be helpful for clarifying, why for different types of test series, evaluated according to the current version of ASTM E1921, differences of up to 30K for $T_{0,X}$ were determined ($X$ is defined as the order of magnitude of $dK/dt$). Different loading rates may be one factor.

With the proposed definition the loading rate of each test can be checked to be within the scope. If not, in some cases censoring may be an option to determine a more accurate reference temperature.

Further experimental and numerical investigations are needed for the validation of this procedure.

The influence of other parameters, such as adiabatic heating in the plastic zone, constraint and small amounts of ductile crack growth will be investigated in the current project.
Conclusion

- Sensitivity to loading rate is too high to allow the mixing of fracture toughness values determined over one total order of magnitude. Proposal: use 2 digits of the logarithm of the loading rate ($T_{0.53}$ resp. $T_{0.58}$).

- Even if only results with the same loading rate are used, the shape of the mastercurve is different from the one used in ASTM E1921 for test series at elevated loading rates.

- First analyses show a good agreement using an exponent of $p=0.03$ instead of $p=0.019$.

- But: $p=0.03$-shape seems not to be applicable in the lower shelf at temperatures 30 K below $T_0$.

- Range for the determination of $T_{0,X}$ has to be narrowed in comparison to the $T_0$ +/- 50K range used in ASTM E1921. Proposal: $T_{0,X}$ +/- 25K.
Acknowledgement

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Rate-sensitivity of the MC-shape and its effect on the uncertainty of $T_0$

Hans-Jakob Schindler
Mat-Tec AG, Winterthur, Switzerland
Contents

- Evidence of rate-dependence of Master Curve
- Effects of loading rate on $T_0$
- Possibilities to account for rate-dependence of MC in E1921
**K\textsubscript{Jc} from tests at elevated loading rates**

**Material:** RPV-steel 22NiMoCr3

Under elevated loading rates the median K\textsubscript{Jc}(1T)-curve does not follow $K_{Jc} = 30 + 70 \cdot e^{0.019(T-T_0)}$

Actual shape: $K_{Jc} = 30 + 70 \cdot e^{p(T-T_0)}$

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ASTM-Workshop Anaheim
Representative loading rate:

mean $\frac{dK_J}{dt}$ in range $5 \text{ MP} \cdot \text{m}^{0.5} < K_J < 30 \text{ MP} \cdot \text{m}^{0.5}$:

$$\dot{K}_{J/ref} = \frac{1}{25} \int_{5}^{30} \frac{dK_J}{dt} dK_J$$
Rate-dependence of Exponent $p$

Determination of $p$ from:

$$\ln(K_{JC/med(1T)} - 30) = \ln C + p \cdot T$$

Results:
Effect of test-temperature on $T_0$ for $p > 0.019$
(for single-temperature testing acc. E1921))

$$T_0 - T_{100} = (T_{test} - T_{100}) \cdot \left(1 - \frac{p}{0.019}\right)$$
$T_0$ of multi-path welds

(a) (b)
Experimental KJc-data of weld material

Loading rate: $\dot{K}_J = 1.40 \text{ MPa} \cdot \text{m}^{0.5}/\text{s}$

Master-Curve TL-Orientierung
SE(B)-Probe

Master-Curve TS-Orientierung
SE(B)-Probe
Variability of $T_0$ through the thickness

**T-L-specimens (0.4T-SEB):**

![Graph showing temperature variation through thickness for T-L-specimens](image1)

**T-S-specimens (0.4T-SEB):**

![Graph showing temperature variation through thickness for T-S-specimens](image2)
Bias with respect to test temperature

T-L-specimens (0.4T-SEB):

T-S-specimens (0.4T-SEB):

Indication that $p > 0.019$

$(p \approx 0.035)$
Shape of MC of Weld Material

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\[ K_{Jc\text{med}}(T) = 30 + 70 \cdot \exp[p \cdot (T - T_0)] \]

- Fits in trend of base material
- Indicates that `p` is not much influenced by yield stress
Reference temperature $T_{100}$ by the OEF-method

$$T_{100} = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{P_{av}} \left[ 4.2485 + P_{av} \cdot T_{test(i)} - \ln(K_{Jc(1T)(i)} - 30) \right]$$

with $P_{av} = 0.032$ (T-L) and 0.039 (T-S), resp.

T-L-specimens (0.4T-SEB)  

T-S-specimens (0.4T-SEB)
Dynamic T0- Data from Boehme et al. 2012

Böhme, W., Mayer, U., Reichert, T., et al. (2012),” IWM-Freiburg, Project No. 150 1368, Report No. 665/2012,
Dynamic T0- data from Joyce, Tregoning & Roe


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Exponent $p$ as a function of loading rate

Simplified trend:

$$p = \begin{cases} 
0.019 & \text{for } \dot{K}_J < 0.5 \\
0.019 + 0.021 \cdot \dot{K}_J & \text{for } 0.5 < \dot{K}_J < 1.25 \\
0.035 & \text{for } \dot{K}_J > 1.25 
\end{cases}$$
Detrimental effects of fixed $p (=0.019)$

- Deterministic influence of test temperature on $T_0$
  - Increases uncertainty of $T_0$
  - Requires extra safety margin in a safety analysis
  - Enables $T_0$ to be manipulated by the choice of test temperature

- Increased uncertainty prevents physical trends from being recognized in experimental data, such as, for examples:
  - Effect of thickness on $T_0$
  - Variation of $T_0$ through the thickness of welds
  - Saturation of rate effects (lower and upper bound)
Conclusions

- p is affected by loading rate for $\dot{K}_J > 0.6 \text{ MPa}\cdot\text{m}^{0.5}/\text{s}$
- For $p > 0.019$, self-consistency of E1921 is violated
- Designability of T0 is not tolerable in a standard
- The problem with $p > 0.019$ should be addressed in E1921, at least as a note or bias.
- Preferably, improvements to reduce this effect should be made
Possibilities for improvements in E1921

1. Providing p as a function of loading rate

Tentatively:

\[
p = \begin{cases} 
0.019 & \text{for } \dot{K}_j < 0.5 \\
0.019 + 0.021 \cdot \dot{K}_j & \text{for } 0.5 < \dot{K}_j < 1.25 \\
0.035 & \text{for } \dot{K}_j > 1.25 
\end{cases}
\]

2. Allowing p to be determined individually by linear regression in a \( \log K_{jc} \)-vs.-T - plot

3. Alternative methods to determine T0
   For example: - CF-method
   - restriction to certain specimen types and sizes
     (to get rid of validity criteria)
Determination of $T_0$ by exponential fit

\[ K_{Jc} = 30 + C \cdot e^{p(T-T_0)} \]

\[ \ln(K_{Jcmed} - 30) = \ln C + p \cdot (T - T_0) \]

\[ T_0 = \frac{\ln(100 - 30) - C}{p} \]

Example: 1T-C(T)-tests:

![Graph showing linear fit and exponential fit for T0 determination](image)
CF-Method

Principle:

Example 1.6T:

Comparison of CF-results from the two most invalid tests with standard T0:
Further changes in Appendix to E1921
Master Curve Analyses of a Dynamic Toughness Round-Robin
IAEA CRP8, 2006-2009

E. Lucon - NIST, Boulder CO (USA)
*formerly at SCK•CEN, Mol (Belgium)

Workshop on “Fracture Toughness Testing and Evaluation at Elevated Loading Rates in the Ductile-to-Brittle Transition Region of Ferritic Steels”
Anaheim CA, 17th May 2015
Round-Robin Exercise (RRE)

- 11 participants signed up (1 did not supply results)
- For each participant: 10 precracked and side-grooved JRQ specimens to be impact tested in the ductile/brittle transition regime
- Impact speed: 1.2 m/s (~10^5 MPa√m/s)
- Minimum response frequency of acquisition system: 100 kHz
- Minimum sampling rate: 2 μs
- Pre-test dimensional measurements: B, B_N, W
- Post-test dimensional measurements: α_o, α_f
- Test procedure: latest ESIS TC5 draft (Dec 2005) and future ISO/ASTM standard → E1921 & E1820 (Annex A17)
Master Curve results supplied by the participants

<table>
<thead>
<tr>
<th>Lab #</th>
<th>N</th>
<th>r</th>
<th>$\Sigma n_i$</th>
<th>$T_0$ (°C)</th>
<th>$\sigma_{T_0}$ (°C)</th>
<th>dK/dt (MPa√m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>9</td>
<td>1.40</td>
<td>-2.3</td>
<td>6.0</td>
<td>3.51E+05</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>9</td>
<td>1.40</td>
<td>1.6</td>
<td>6.0</td>
<td>3.21E+05</td>
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<tr>
<td>3</td>
<td>10</td>
<td>7</td>
<td>1.12</td>
<td>-9.9</td>
<td>6.8</td>
<td>3.70E+05</td>
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<tr>
<td>4</td>
<td>8</td>
<td>8</td>
<td>1.18</td>
<td>10.0</td>
<td>6.6</td>
<td>4.14E+05</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>10</td>
<td>1.57</td>
<td>2.1</td>
<td>5.7</td>
<td>3.29E+05</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>9</td>
<td>1.32</td>
<td>4.6</td>
<td>6.0</td>
<td>3.44E+05</td>
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<tr>
<td>7</td>
<td>10</td>
<td>8</td>
<td>1.33</td>
<td>-20.4</td>
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<td>1.40</td>
<td>-1.1</td>
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<td>3.36E+05</td>
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<td>10</td>
<td>7</td>
<td>1.07</td>
<td>-2.5</td>
<td>6.8</td>
<td>4.25E+05</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>9</td>
<td>1.40</td>
<td>-3.8</td>
<td>6.0</td>
<td>5.02E+05</td>
</tr>
</tbody>
</table>

Average values: 1.32, -2.2, 6.2, 3.66E+05

All participants provided valid $T_0$ measurements

Max difference between individual $T_0 = 30.4$ °C
Normalized representation of RRE Master Curve results

RRE results effectively follow the Master Curve and its tolerance bounds
Overall Master Curve for all available results

<table>
<thead>
<tr>
<th>N</th>
<th>r</th>
<th>$\Sigma n_i$</th>
<th>$T_o$ (°C)</th>
<th>$\sigma_{T_o}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>98</td>
<td>85</td>
<td>13.21</td>
<td>-4.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### Key
- **Overall MC**
- **MC**
- **LB**

### Legend Icons
- #1
- #2
- #3
- #4
- #5
- #6
- #7
- #8
- #9
- #10

### Graph Details
- $K_{Jc,IT}$ (MPa/m)
- Temperature (°C)
Comparison between individual and overall reference temperatures

Outlier lab: $K_{jc}$ too high $\rightarrow$ $T_o$ too low
Effects of removing the outlier laboratory (#7)

- Maximum difference between individual $T_o$ drops to 19.8 °C
- None of the reported $T_o$ is statistically different at the 95% (±2s) confidence level

<table>
<thead>
<tr>
<th>N</th>
<th>r</th>
<th>$\Sigma n_i$</th>
<th>$T_o$ (°C)</th>
<th>$\sigma_{T_o}$ (°C)</th>
<th>dK/dt (MPa√m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>77</td>
<td>11.98</td>
<td>-0.8</td>
<td>2.1</td>
<td>3.77E+05</td>
</tr>
</tbody>
</table>
Common reanalysis of RRE results by ForschungsZentrum Rossendorf (individual $K_{jc}$ and $T_o$)

<table>
<thead>
<tr>
<th>Lab #</th>
<th>$T_{o,or}$ (°C)</th>
<th>$T_{o,recalc}$ (°C)</th>
<th>Δ$T_o$ (°C)</th>
<th>Δ$K_{jc}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.3</td>
<td>3.5</td>
<td>-5.8</td>
<td>9.1</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>3.7</td>
<td>-2.1</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>-9.9</td>
<td>-5.2</td>
<td>-4.6</td>
<td>17.5</td>
</tr>
<tr>
<td>4</td>
<td>10.0</td>
<td>1.6</td>
<td>8.4</td>
<td>-3.3</td>
</tr>
<tr>
<td>5</td>
<td>2.1</td>
<td>1.7</td>
<td>0.4</td>
<td>-2.6</td>
</tr>
<tr>
<td>6</td>
<td>4.6</td>
<td>11.8</td>
<td>-7.2</td>
<td>18.0</td>
</tr>
<tr>
<td>7</td>
<td>-20.4</td>
<td>-22.3</td>
<td>1.9</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>-1.1</td>
<td>-1.3</td>
<td>0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>9</td>
<td>-2.5</td>
<td>11.3</td>
<td>-13.8</td>
<td>28.5</td>
</tr>
<tr>
<td>10</td>
<td>-3.8</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
<tr>
<td>Average</td>
<td>-2.2</td>
<td>0.5</td>
<td>-2.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Large differences due to:

- **Elastic component**: different values of $E$ and anvil span $S$
- **Plastic component**: different interpretation of specimen compliance
Possible requirement on the time to fracture ($t_f$)

- ISO & ASTM drafts at the time required for a quasi-static evaluation: $t_f > 5\tau$ (i.e. fracture after 5 oscillations)
- Previously (Ireland et al, EPRI – 70’s): $t_f > 3\tau$
- With:

$$\tau = 3.36 \cdot \left( \frac{W}{S_0} \right) \cdot \sqrt{E' \cdot B_N \cdot C_S}$$

- If the requirement is not fulfilled → a quasi-static evaluation (i.e. E 1820-type) cannot be used, and dynamic methods are required
- For RRE specimens, $\tau = 54.7 \mu s$ and therefore:

$$3\tau = 164 \mu s \text{ and } 5\tau = 274 \mu s$$
Re-analysis of the RRE results according to the \( \tau \) requirement

- 48 out of 98 tests (49%) do not satisfy the more stringent criterion \((t_f > 5\tau)\)
- Only 8 out of 98 tests (8%) do not satisfy the less stringent criterion \((t_f > 3\tau)\)
- Effect on Master Curve analyses

Replacing \( K_{J_c} \) with the value at \( 3\tau \) (52.5 MPa\(\sqrt{m} \)) or at \( 5\tau \) (90 MPa\(\sqrt{m} \))

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Action</th>
<th>( N )</th>
<th>( r )</th>
<th>( \sum n_i )</th>
<th>( T_o ) ((^\circ)C)</th>
<th>( \sigma T_o ) ((^\circ)C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>None</td>
<td>98</td>
<td>85</td>
<td>13.21</td>
<td>-4.2</td>
<td>2.0</td>
</tr>
<tr>
<td>( t_f &gt; 3\tau )</td>
<td>Remove data</td>
<td>90</td>
<td>77</td>
<td>12.02</td>
<td>-5.3</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>&quot;Censor&quot; data</td>
<td>98</td>
<td>77</td>
<td>12.02</td>
<td>-5.4</td>
<td>2.1</td>
</tr>
<tr>
<td>( t_f &gt; 5\tau )</td>
<td>Remove data</td>
<td>50</td>
<td>37</td>
<td>6.14</td>
<td>-13.4</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>&quot;Censor&quot; data</td>
<td>98</td>
<td>37</td>
<td>6.17</td>
<td>-17.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- Application of the more stringent requirement can yield significantly lower (i.e. non-conservative) \( T_o \).
Conclusions drawn from the Round-Robin Exercise (1)

- Results supplied by the participants were very consistent and showed reasonable scatter.
- The Master Curve approach was proven to be fully applicable to impact fracture toughness measurements obtained in the ductile-to-brittle transition region.
- The quality of impact fracture toughness measurements strongly depends on the quality of instrumented force values. Hence, a reliable calibration of the instrumented striker is of primary importance.
Conclusions drawn from the Round-Robin Exercise (2)

• The guidelines provided by ISO/ASTM draft procedures and followed by RRE participants for test execution and data analysis proved to be reliable and easy to implement.
• The radius of the instrumented striker (2 mm or 8 mm) had negligible influence on the measured $T_o$. 
Recommendations for future work

• Establish correlations between crack arrest toughness ($K_{la}$) and dynamic/impact fracture toughness ($K_{ld}$).
• Compare lower bound Master Curves (corresponding to low fracture probabilities) obtained from dynamic/impact toughness measurements with the ASME $K_{IR}$ lower bound curve.
• Determine an “equivalent” dynamic $RT_{To,dyn}$ (similar to ASME Code Cases N-629 and N-631) for indexing the ASME lower bound $K_{IR}$ curve.
Full details in:

Estimation of the loading rate
Kim Wallin VTT

Workshop on Fracture Toughness Testing and Evaluation at Elevated Loading Rates in the Ductile-to-Brittle Transition Region of Ferritic Steels.
The ASTM E1921 testing standard contains loading rate estimates for the SE(B) and C(T) specimens. It must be emphasized that the estimates are only valid for a case of linear-elastic loading, or in the linear part of the load-displacement curve. The estimates are in the standard given in a tabulated form only, but they are based on the principle represented by Eqs. They perform a simple transformation of displacement into load via the compliance function and the transformation of load to stress intensity factor via the standard $K_I$ calibration functions.

$$\dot{K}_{I-E1921} = \dot{\Delta} \cdot \frac{E \cdot S / W \cdot f(a/W)}{\sqrt{W \cdot C_{LL}(a/W)}}$$ : SE(B)

$$\dot{K}_{I-E1921} = \dot{\Delta} \cdot \frac{E \cdot f(a/W)}{\sqrt{W \cdot C_{LL}(a/W)}}$$ : C(T)
Elastic plastic case

In the elastic regime, there is a linear dependency between specimen displacement rate and fracture mechanical loading rate, but this dependency is lost with the development of plasticity in the specimen. The linear-elastic equations overestimate the loading rate, when the specimens experience plasticity. Accounting for the effect of plasticity on the loading rate requires a relation between elastic-plastic crack driving force and total displacement.

\[
(a / W > 0.4) : J_{SE(B)} \approx (W - a) \cdot 1.4 \cdot \sigma_f \cdot \left(\frac{\Delta}{W}\right)^{1+140 \text{MPa}}
\]

\[
(a / W > 0.5) : J_{C(T)} \approx (W - a) \cdot 1.4 \cdot \left(1.6 - 0.6 \cdot \frac{a}{W}\right) \cdot \sigma_f \cdot \left(\frac{\Delta}{W}\right)^{1+140 \text{MPa}}
\]
Post test estimate

Lucon and Scibetta concluded that the optimum post test loading rate estimate is simply obtained by dividing the fracture toughness value with the time needed to reach the fracture toughness. This “average” loading rate corresponded very well to the mean value of dK/dt during the test. They did note, however, that the “average” loading rate cannot be estimated for tests containing e.g. partial unloadings.

A new analytical procedure is presented here. It can be used to estimate either the instantaneous or average loading rate allowing for unloadings.
New analytical procedure

\[
\dot{K}_{est} \approx \sqrt{1.4 \cdot b \cdot \sigma_f \cdot E'} \cdot \left(0.5 + \frac{70\text{MPa}}{\sigma_f}\right) \cdot \left(\frac{\dot{\Delta}}{W}\right) \cdot \left(\frac{0.5 \cdot \sigma_f - 70\text{MPa}}{140\text{MPa} + \sigma_f}\right)
\]

SE(B) \quad \frac{a}{W} = 0.3...0.7

\[
\dot{K}_{est} \approx \sqrt{1.4 \cdot b \cdot \left(1.6 - 0.6 \cdot \frac{a}{W}\right) \cdot \sigma_f \cdot E'} \cdot \left(0.5 + \frac{70\text{MPa}}{\sigma_f}\right) \cdot \left(\frac{\dot{\Delta}}{W}\right) \cdot \left(\frac{0.5 \cdot \sigma_f - 70\text{MPa}}{140\text{MPa} + \sigma_f}\right)
\]

C(T) \quad \frac{a}{W} = 0.4...0.7
Comparison of relation between elastic-plastic and linear-elastic loading rate estimates.

Lucon and Scibetta data
Comparison of elastic-plastic loading rate estimate with experimental “average” loading rate estimate

Lucon and Scibetta data
Comparison of mean elastic-plastic loading rate estimate with experimental “average” loading rate estimate

Lucon and Scibetta data
Conclusions

It is debateable whether the mean loading rate or the instantaneous loading rate is the more appropriate parameter to describe loading rate. The difference between the two can, in the worst situation, be of the order of 50%. This difference is still comparatively small when considering the effect of loading rate on fracture toughness.
Statistical Distribution of Dynamic Fracture Toughness Values, Shape of Dynamic Master Curves and Crack Tip Loading Rates

Implications for a High Rate Appendix of ASTM E1921

Workshop on Fracture Toughness Testing and Evaluation at Elevated Loading Rates in the Ductile-to-Brittle Transition Region of Ferritic Steels
Sponsored by E080706 Task Group on Ductile-Brittle Transition
Anaheim, May 17th, 2015

Wolfgang Böhme
Thomas Reichert
Johannes Tlatlik

Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany (wolfgang.boehme@iwm.fraunhofer.de)
Experience obtained during two joint projects of Fraunhofer IWM (Freiburg) & MPA (Stuttgart)

„Dynamic Master-Curves (MC) for high loading rates“
(Phase 1 in 2010-2013 and Phase 2 in 2014-2016)

Determination of Dynamic Fracture Toughness Values $K_{jc,d}(T, \frac{dK}{dt})$

at elevated crack tip loading rates:

$\frac{dK}{dt} = 3 \times 10^3 \text{ MPa m}^{0.5} \text{ s}^{-1} \ldots \ldots 5 \times 10^6 \text{ MPa m}^{0.5} \text{ s}^{-1}$

according to ASTM E1820 and E1921

Results will be presented in more detail at the ASTM/ESIS-conference this week:

- Mayer (MPA/Stuttgart) Thursday, May 21st, 1:30 PM
- Böhme & Reichert (IWM/Freiburg) Thursday, May 21st, 2:20 PM
Material and Specimens

22 NiMoCr 3 7 (similar to A 508 Cl.2)
originally provided for Biblis C
and well qualified

\( T_{0,\text{stat}} = -68 \, ^\circ\text{C} \)
\( \text{RT}_{\text{NDT}} = -20 \, ^\circ\text{C} \)

Material is the same as in previous investigations on quasistatic Master Curves:


High Rate Experiments and Measuring Techniques
Crack Mouth Opening Displacement CMOD

MPA

IWM

Digital Image Correlation (DIC: ARAMIS) to measure CMOD

SE(B) 40/20, $v_0 = 0.6 \text{ m/s}$, $\frac{dK}{dt} = 2 \times 10^5 \text{ MPa} \sqrt{\text{m} \text{s}^{-1}}$, $T = -20\degree\text{C}$

© Fraunhofer-Institut für Werkstoffmechanik IWM
Dynamic Fracture Toughness $K_{Jc,d}$ Evaluation at Elevated Loading Rates

- Determination of $K_{Jc,d}$ based on locally measured Force- and CMOD-signals
- Evaluation of the Force-CMOD curve according to ASTM E1921
Force-Time Curves
SE(B)10/10, a/W = 0.3, T = -20 °C

- \( v_0 = 0.6 \text{ m/s} \)
- \( dK/dt = 2 \times 10^5 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1} \)
- \( t_W \)
  - Global force by piezo load cell of VHS

- \( v_0 = 1 \text{ m/s} \)
- \( dK/dt = 3 \times 10^5 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1} \)
- \( t_W \)
  - Global force by instrumented tup of the pendulum impact machine according to ISO 14556

- \( v_0 = 6 \text{ m/s} \)
- \( dK/dt = 3 \times 10^6 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1} \)
- \( t_W \)
  - Local force by near crack tip strain gauge

\( \Rightarrow \) ASTM E1820 requirement \( t_f > t_W \) violated at \( dK/dt = 3 \times 10^6 \text{ MPa} \sqrt{\text{m}} \text{ s}^{-1} \)
Force vs. Displacement (LLD) or CMOD
SE(B)10/10, a/W = 0.3, T = -20 °C

Even at $\frac{dK}{dt} = 3 \cdot 10^6$ MPa$\sqrt{m}$ s$^{-1}$, the local measurements result in F(CMOD)-curves which can be evaluated according to ASTM E1921
High Rate Fracture Toughness $K_{Jc,d}$

5% Lower Bound Curves vs. Temperature

- $K_{Jc,d}(1T)$-data and corresponding 5%-MC’s of all dynamic tests at various crack tip loading rates $dK/dt$
- Quasistatic $K_{Jc,5\%}$
- Rate-dependent $K_{Jc,d,5\%}$
- $K_{IR}$ lower bound curve

All fracture toughness data meet the validity requirements of ASTM E1921

All fracture toughness values $K_{Jc,d}(1T)$ are above the $K_{IR(\Delta T_{NDT})}$ curve

Some 5%-fractile curves are below the $K_{IR(\Delta T_{NDT})}$-curve
High Rate Reference Temperatures $T_{0,X}$ vs. $dK/dt$

- Dynamic Master Curve reference temperature $T_{0,X}$ vs. loading rate
  - $T_{0,X}$: Rate dependent reference temperature evaluated based on Weibull distribution (according to ASTM E1921)
  - $T_{0,KIR}$: $K_{IR}$-corresponding Master Curve reference temperature,

**ASTM E1921 estimate:**

$$T_{0,x}^{est} = \frac{(T_{0,stat.} + 273,15) \cdot \Gamma}{\Gamma - \ln(X)} - 273,15$$

with

$$\Gamma = 9.9 \exp \left( \frac{T_{0,stat.} - 273,15}{190} \right)^{1.66} + \left( \frac{\sigma_{YS},stat.}{722} \right)^{1.09}$$

⇒ ASTM E1921 estimate is reasonable for some but not for all series of tests!

⇒ Are there two distinct collectives: a brittle and a more ductile one???
Correction to $T_{0,\text{est.}}$. 

- Estimated value of $T_{0,X}$

\[
T_{0,dyn}(X) = T_{0,X} = \frac{(T_{0,\text{stat}} + 273,15) \cdot \Gamma}{\Gamma - \ln(X)} - 273,15
\]

ASTM E 1921-14a eq. (3)

with

\[
\Gamma = 9,9 \cdot \exp\left(\frac{T_{0,\text{stat}} + 273,15}{190}\right)^{1,66} + \left(\frac{\sigma_{\text{YS}}}{722}\right)^{1,09}
\]

ASTM E 1921-14a eq. (4)

and

\[
X = \frac{\Delta K}{\Delta t} \text{ in MPa}\sqrt{\text{ms}^{-1}}
\]

Correction to $T_{0,\text{est.}}$. 

Corrected:

- ASTM E1921-11a estimate (with $T_{0,\text{stat.}} = -68^\circ\text{C}$, $\sigma_S(\text{RT})$)
- ASTM E1921-11a estimate (with $T_{0,\text{stat.}} = -68^\circ\text{C}$, $\sigma_S(T_{0,\text{stat.}})$)
High Rate Fracture Toughness Data vs. \( T-T_0 \)

- Fracture toughness values \( K_{Jc,d}(1T) \) of all dynamic tests normalized to \( T_0 \)
- and 5\%- , 50\%- and 95\%-fractile Master Curves

⇒ All fracture toughness data meet the validity requirements of ASTM E1921
Deviation of High Rate Reference Temperature from ASTM-Estimate: $T_{0,X} - T_{0,\text{est}}$

- two collectives?
- bimodal fracture?
Statistical Analysis

- Statistical distribution of fracture toughness $K_{Jc,d}(1T)$ values
  - data set with 32 dynamic SE(B)10/10-tests at $\frac{dK}{dt} \approx 3 \cdot 10^5$ MPa$\sqrt{m} \cdot s^{-1}$

The lognormal-distribution is in better agreement with the experimental data set compared to the Weibull-distribution of ASTM E1921 ($b = 4$, $K_{min} = 20$ MPa$\sqrt{m}$)
Alternative $T_{0,x}$-Evaluation

Lognormal-Distribution

- Alternative Master Curve evaluation assuming a lognormal-distribution (with $\sigma = 0.21$, determined from the statistical analysis)

⇒ Some of the 5%-curves are still below the $K_{IR(\text{RT}_{\text{NDT}})}$ curve at higher temperatures
Alternative $T_{0,x}$-Evaluation
Shape of High Rate Master Curves

Alternative Master Curve evaluation with rate-dependent shape factor $p$

Adjustment of value $p$ is based on a multi-temperature Master Curve evaluation of a large data set of test results [3] with

- different SE(B) specimen widths: 0.4T, 0.8T, 1.6T and 3.2T
- crack loading rates up to $\approx 10^5$ MPa$\sqrt{m}$ s$^{-1}$

$$K_{J_c,med}(T) = 30 + C \cdot e^{p(T-T_0)}$$

⇒ A value of $p = 0.030$ was used below for alternative dynamic Master Curve evaluations
Alternative $T_{0,x}$-Evaluation

Shape of High Rate Master Curves

- Comparison of MC-evaluation according to ASTM 1921 with alternative MC-evaluation with $p = 0.030$

- Two SE(B) 40/20 test series at two different test temperatures and comparable crack loading rate $dK/dt = 3 \cdot 10^6$ MPa$\sqrt{m}$ s$^{-1}$ and $5 \cdot 10^6$ MPa$\sqrt{m}$ s$^{-1}$

$\Rightarrow$ improved description for both series of tests with $p = 0.030$
Discussion

Alternative $T_{\text{0,x}}$-Evaluation, MC-shape

- Alternative Master Curve evaluation with $p = 0.030$

$\Rightarrow$ 5% Master Curves are now above the $K_{\text{IR(\text{RT}_{\text{NDT}})}}$ curve and closer to the data

SE(B)-Results: IWM/Freiburg
C(T)-Results: MPA/Stuttgart
High Rate Fracture Toughness $K_{Jc,d}$
5% Lower Bound Curves vs. Temperature

Best approach so far: Weibull und $p = 0.030$
Proposals on the Evaluation of High Rate Tests

Our results lead to the following

**Suggestions on a High Rate Appendix of ASTM E1921:**

- In addition to the “quasistatic evaluation” based on the Weibull distribution it should be opened to other statistical evaluations:
  - e.g.: lognormal, as in ASTM E1221 (Crack Arrest),

and/or

- it should be opened to a rate dependent shape factor “p”:
  - e.g.: as proposed by Schindler/Kalkhof
    in order to take into account adiabatic heating at the crack tip
Crack Tip Loading Rate \( \frac{dK}{dt} \) or \( \frac{dJ}{dt} \)

Definitions According to Various Standards

**BS 7448-3 (2005)**

\[
\frac{dK}{dt} = \text{slope of } K(0.5F_A) \text{ till } K(F_A)
\]

\[
F
\]

\[
F_c
\]

\[
F_A
\]

\[
0.5F_A
\]

\[
t_p
\]

**ASTM E1921 (2014)**

\[
\frac{dJ_P}{dt} \text{ with } t_p \text{ and plastic work } U_p
\]

\[
F
\]

\[
F_c
\]

\[
K_J
\]

\[
t_f
\]

\[
K_{Jc,d}
\]

**ASTM E1820 (2013)**

\[
\frac{dK}{dt} = \frac{K_{Jc,d}}{t_f}
\]

\[
J
\]

\[
J_Q
\]

\[
t_Q
\]

\[
0.5J_Q
\]

\[
\text{onset of stable crack extension}
\]

\[
\text{linear fit}
\]

\[
(dJ/dt)_I = \text{slope of } 0.5J_Q \text{ till } J_Q
\]

\[
(dJ/dt)_T = \text{slope of } J_Q \text{ till } J_Q + 0.5(J_{max} - J_Q)
\]
Idea: Definition of crack tip loading rate similarly to ISO 26203-2 (2011)

Metallic materials — Tensile testing at high strain rates —
Part 2: Servo-hydraulic and other test systems

The various definitions of strain rates such as

- the time-dependent strain rate (3),
- the characteristic strain rate (2), and
- the limits for a high rate test at a sufficient constant strain rate (dashed box)

are adopted from:


⇒ Idea: Development of similar definitions for the crack tip loading rate for the high rate appendix of ASTM E1921
Evaluation of Crack Tip Loading Rates based on $K_J(t)$
Evaluation of Crack Tip Loading Rates based on J(t)
Proposal on the Crack Tip Loading Rate

- Calculation of a nominal value: $dK/dt|_{nom}$ (based on $v_0$ and specimen size)
- Evaluation of the actual $dK_J/dt(t)$-curve: $dK_J/dt(t)|_{actual}$
- Determination of a characteristic value, e.g.: $dK_J/dt|_{char} = \text{mean } \{dK_J/dt (t = t_{0.5FA} \ldots t_{FA})\}$
- Validity-Requirement: $|dK_J/dt(t)|_{actual} - dK_J/dt|_{char} | < 0.40 \times dK_J/dt|_{char}$
Summary
Proposals for ASTM E1921 Annex “High Rate”

Our results lead to the following suggestions:

- In addition to the “quasistatic evaluation” based on the Weibull distribution, the high rate appendix should be opened to other statistical evaluations:
  - E.g.: lognormal, as in ASTM E1221 (Crack Arrest)

- Rate dependent shape factor “p”, as proposed by Schindler/Kalkhof in order to take into account adiabatic heating at the crack tip

- The definition of the crack loading rate \( \frac{dK}{dt} \) should be extended:
  - Calculation of a nominal value: \( \frac{dK}{dt}_{\text{nom}} \)
  - Evaluation of the actual \( \frac{dK}{dt}(t) \)-curve: \( \frac{dK}{dt}(t)_{\text{actual}} \)
  - Determination of a characteristic value, e.g.: \( \frac{dK}{dt}_{\text{char}} = \text{mean} \{ \frac{dK}{dt}(t = t_{0.5FA} \ldots t_{FA}) \} \)
  - Validity-Requirement: \( |\frac{dK}{dt}(t)_{\text{actual}} - \frac{dK}{dt}_{\text{char}}| < 0.40 \times \frac{dK}{dt}_{\text{char}} \)
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Thank you for your attention!