Modified Shape of Dynamic Master Curves due to Adiabatic Effects

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Abstract

Within a joint project of IWM/Freiburg and MPA/Stuttgart the fracture toughness of a 22 NiMoCr 37 steel (A 508 Cl.2) was characterized at IWM with SE(B)10/10- und SE(B)40/20-specimens at -20 °C and high crack loading rates in the range of 10^3 to 10^6 MPa/μm s^{-1}, see Böhme et al. (2012 and 2013). The single temperature Master Curve evaluation according to ASTM E1921 and Wallin (2011) resulted in part in 5%-lower-bound fracture toughness versus temperature curves below the deterministic ASME lower bound K_{IR}-reference-curve. At a first glance, this seems to violate the ASME K_{IR}-concept, however, possibly this just indicates, that the conventional MC-evaluation has to be modified for elevated loading rates. Adiabatic heating in the vicinity of the crack tip could be one reason for that, as already argued in Schindler (2013 and 2015).

Therefore, additional SE(B)-tests at temperatures of -20 °C, 0 °C and +20 °C were performed at IWM within the current follow-up joint IWM-MPA project. The new IWM-results show in agreement with previous investigations by Viehreig et al. (2010) and Schindler et al. (2013 and 2015) that the Master Curves at elevated loading rates are steeper than at quasistatic loading, probably due to local adiabatic heating in the vicinity of the crack tip. Therefore, the temperature field around the crack tip has been measured with a high speed infrared camera and has been compared to results of a numerical simulation. Up to crack initiation, a local adiabatic rise in temperature of the order of magnitude of about 60 K was measured and calculated in the vicinity of the crack tip at a crack loading rate of about 10^6 MPa/μm s^{-1}. In order to take into account this adiabatic effect, the dynamic master curves were evaluated by applying an adjusted MC shape parameter. This finally leads to more plausible results for the dynamic Master Curves. Thus, the choice of a rate dependent shape parameter p should be considered for future modifications of the elevated loading rate appendix of ASTM E1921.

Keywords: Fracture mechanics; high loading rates; dynamic Master Curve; K_{IR}-curve

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1. Introduction

In the safety assessment of reactor pressure vessels, the $K_{IR}$-reference curve is deemed to be the limiting lower bound curve for fracture toughness and crack arrest values. One aim in a joint project between Fraunhofer IWM Freiburg and MPA university of Stuttgart was to assess the applicability of this limiting curve to characteristic fracture values $K_{JC,d}$ determined according to the Master Curve concept at elevated loading rates and further how these initiation values range in comparison to crack arrest values $K_{IA}$ and the $K_{IR}$-curve.

Therefore, numerous dynamic fracture tests have been performed with bend specimens of two sizes up to high crack tip loading rates of $dK/dt \approx 10^7$ MPa$\cdot$m s$^{-1}$ and characteristic crack initiation values for dynamic loading $K_{JC,d}$ as well as Master Curve reference temperatures $T_0$ ($dK/dt$) according to the Master Curve(MC) concept have been determined using specially developed highspeed measuring and test technique. Since the obtained dynamic fracture toughness values $K_{JC,d}$ ($T$, $dK/dt$) as expected decline from quasistatic results with increasing crack tip loading rate but still lie above the $K_{IR}$-reference curve, see Fig. 1, the conservatism of the $K_{IR}$-curve has been confirmed. With increasing crack tip loading rate, the individual toughness values are lower and the resulting 5%-fractile Master Curves are shifted towards higher temperatures up to 90 K. Consequently, they are below the $K_{IR}$-curve at higher temperatures, see Fig. 1.

Further, two test series at different test temperatures indicate a steeper form of the Master Curve at dynamic loading, see Böhme (2015). Evidence of such adjusted Master Curve can also be found for other investigations e.g. Schindler et al. (2013 and 2015). One possible explanation for a steeper slope is the adiabatic heating in the vicinity of the crack tip.

Thus, further dynamic fracture mechanic tests with SE(B)40/20 specimens have been performed in the current joint project between IWM and MPA for a greater range of temperatures of -20 °C, 0 °C and +20 °C and at crack tip loading rates of $dK/dt = 3 \times 10^3$ and $3 \times 10^5$ MPa$\cdot$m s$^{-1}$. Master Curve reference temperatures $T_{0,X}$ have been determined with single- and multi-temperature evaluation according to ASTM E1921. Additionally, adiabatic heating in the vicinity of the crack has been recorded with a highspeed infrared camera and the local strain field has been measured with digital image correlation analysis (ARAMIS) for SE(B)40/20 tests at a crack tip loading rate of $dK/dt = 3 \times 10^5$ MPa$\cdot$m s$^{-1}$. The tests have also been simulated numerically taking into account adiabatic heating and thermal conduction.

### Nomenclature

- **$a$**: crack length, mm
- **CMOD**: crack mouth opening displacement, mm
- **$dK/dt$**: crack tip loading rate, MPa$\cdot$m s$^{-1}$
- **$F$**: force, kN
- **$K_{IA}$**: fracture arrest toughness, MPa$\cdot$m
- **$K_{IR}$**: fracture toughness, MPa$\cdot$m
- **$K_{JC,d}$**: dynamic fracture toughness, MPa$\cdot$m
- **$RT_{NDT}$**: Nil Ductility Transition Reference Temperature, °C
- **$T_0$**: test temperature, °C
- **$T_0,static$**: quasistatic Master Curve reference temperature, °C
- **$T_0,X$**: Master Curve reference temperature at crack tip loading rate X, °C
- **$T_{0,X,static}$**: Multi-temperature Master Curve reference temperature at crack tip loading rate X, °C
- **$T_{0,X,static}$**: Single-temperature Master Curve reference temperature at crack tip loading rate X, °C
- **$W$**: specimen width, mm
- **$X$**: first two digits of the logarithm of the crack tip loading rate, X$=\log_{10}(dK/dt)$
Fig. 1. Fracture toughness $K_{Ic,d}$ and 5%-fractile lower bound curves according to ASTM E1921 of all test series of the previous project with varying specimen sizes and varying loading rates compared to the $K_{Ic}$-curve, SE(B) results from IWM and $C(T)$ results from MPA.

2. Specimens and material

The fracture mechanics tests have been performed with reactor pressure vessel steel 22 NiMoCr 3 7, which had been used in other investigations on the applicability of the Master Curve concept at quasistatic loading rates Hohe et al. (2005) and Roos et al. (2006) and in the preceding project Böhme et al (2012). Results obtained were the characteristic Master Curve reference temperature for quasistatic loading $T_{0,\text{stat}} = \text{-}68 \degree\text{C}$ and a “Nil Ductility Transition Reference Temperature” of $RT_{NDT} = \text{-}20 \degree\text{C}$.

In the current project specimens have been extracted similar to Hohe et al. (2006) with cracks positioned between $\frac{1}{3}$ and $\frac{2}{3}$ of the vessel’s thickness and with a crack orientation perpendicular to the vessel’s longitudinal axis, thus simulating a crack starting from inside the vessel towards the outer surface (T-S-orientation).

All SE(B)-specimens were pre-cracked according to ASTM E1921 with a stress intensity factor $K_I$ of below 15 MPa$\sqrt{m}$ for the final 0.6 mm crack growth. The initial crack depth before testing was $a/W = 0.3$, which is the minimum ratio allowed by ISO/DIS 26843 in order to minimize impact induced vibrations and to obtain a linear increase in crack tip loading, see Böhme (1990). Specimens received 10% side grooves on each side, in order to achieve a relative straight crack front and a relative constant stress constraint along the crack front.

3. Experiments and measuring techniques

Experiments with SE(B)40/20 specimens were performed at a 500kN rapid tensile testing machine with a three-point bending test rig, see Fig. 2. For the evaluation of dynamic $K_{Ic,d}$ values according to ASTM E1921 and ASTM E1820 a load-crack mouth opening plot is required. Due to inertia effects, global force measurements at high loading velocities show oscillations, which cannot be used in an evaluation of the fracture toughness value. Therefore, a local type of force measurement was used with strain gauges applied close to the vicinity of the crack tip according to Böhme et al. (1983) and in the quarter point of the bending specimen according to ASTM E1820. Each measurement uses signals from two opposing strain gauges which have been averaged to mitigate any effect resulting from slightly asymmetric loading, see Fig. 2. In order to obtain a useable force signal at higher loading rates, a calibration of the strain gauge signals at a medium loading rate, at which inertia effects do not affect the measured global force, has been performed. The crack mouth opening displacement $CMOD$ has been determined.
with high-speed camera and the digital image correlation (DIC) system ARAMIS by measuring the relative movement of the flanks of the crack.

![Diagram of test setup](image)

Fig. 2. Left: High-speed test- and measurement-technique with instrumented SE(B) bending specimen and exemplary evaluation of a locally determined force-CMOD-signal. Right: high-speed IR-camera for SE(B)-bending tests in a high rate testing machine.

For an additional test series, a second high-speed camera was used to measure the local strains in the vicinity of the crack tip. Furthermore, a high-speed infrared camera has been applied to obtain the local temperature field near the crack tip at the opposite side of the specimen. The camera is able to record images at a frame rate of 15 kHz, which allowed for sufficiently capturing the development of the temperature field for fracture mechanics tests with times-to-fracture of around 1 millisecond.

4. Results

4.1. Dynamic Master Curve reference temperatures $T_{0,X}$

Each test resulted in an individual fracture toughness value $K_{Jc,d}(T, dk/dt)$. All determined dynamic fracture toughness values were valid according to ASTM E1921: individual $K_{Jc,d}$ did not exceed $K_{Jc,d,limit} \{T, \sigma_{YS}(T, dk/dt)\}$ providing small scale yielding, ductile crack extension $a_p$ was less than the allowed 1.0 mm and test temperatures $T$ and reference temperatures $T_{0,X}$ were within the limits of $-50 \, ^\circ C \leq T-T_{0,X} \leq +50 \, ^\circ C$.

In order to take into account different specimen sizes and thus crack widths, the fracture toughness values were normalized to a standard C(T) specimen width of $1T = 25$ mm. For each test series at a certain temperature $T$ and loading rate $dk/dt$ a reference temperature $T_{0,X,single}$ was determined according to the ASTM E1921 single-temperature method. Additionally, for each loading rate, tests at different temperatures combined resulted in a multi-temperature reference $T_{0,X,multi}$-value. The index $X$ in the reference temperature refers to the logarithm $\log_{10}$ of the respective crack tip loading rate $dk/dt$. The equation for the median Master Curve depends only on this reference temperature $T_{0,X}$:

$$K_{Jc(med)}(T) = 30 + 70e^{(T-T_{0,X})}$$

(1)

The shape parameter $p$ is set to 0.019 as stated in the ASTM standard.
The obtained $K_{jc,d}(IT)$ values versus the test temperature $T$ are presented in Fig. 3 for an intermediate (left) and for a higher loading rate (right). Next to these individual fracture toughness values (colored diamonds), the calculated median value, based on an assumed Weibull distribution according to ASTM E1921, is plotted as well for each test series (open diamonds). The resulting Master Curve reference temperature $T_{0,X,\text{single}}$ (colored values), according to the single-temperature method, is listed alongside these median values. The reference temperature $T_{0,X,\text{multi}}$ including all series tested at different temperatures, using the multi-temperature evaluation, is given at the lower right hand side of each diagram. The resulting median- and 5%-Master Curves (black dashed lines) are plotted next to the respective curves for quasistatic loading (grey dashed lines). For comparison the lower bound $K_{IR}$-curve is plotted as well.

When comparing the median values for each individual test series with the multi-temperature Master Curve, the results indicate for both loading rates a steeper course of the actual curve. Consequently, individual reference temperatures, determined with the single-temperature method, differ greatly from each other and differences range between ca. 15 K (medium loading rate) and around 30 K (high loading rate).

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Fig. 3. Median- and 5%-Master Curves with $p = 0.019$ for five dynamic SE(B) test series; left: $v_0 = 0.025$ m/s, $dK/dt = 3 \times 10^3$ MPa$\sqrt{m}$ s$^{-1}$, right: $v_0 = 2.5$ m/s, $dK/dt = 3 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$.

Fig. 4. Median- and 5%-Master Curves with $p = 0.030$ for five dynamic SE(B) test series; left: $v_0 = 0.025$ m/s, $dK/dt = 3 \times 10^3$ MPa$\sqrt{m}$ s$^{-1}$, right: $v_0 = 2.5$ m/s, $dK/dt = 3 \times 10^5$ MPa$\sqrt{m}$ s$^{-1}$.
Considering a steeper course for the Master Curves the shape parameter $p$ has been adjusted to 0.030, as already suggested in Böhme et al (2012) analog to the advanced Master Curve according to Wallin (2011). With this alteration the Master Curves better fit the fracture toughness values and their corresponding median values for the medium and higher crack tip rate, as can be seen in Fig. 4. Consequently, the individual reference temperatures $T_{0,X,single}$ converge to the respective $T_{0,X,multi}$-value obtained from the multi-temperature evaluation and vary only around ±5 K.

4.2. Strain field and local adiabatic heating in the vicinity of the crack tip

One reason for this steeper slope presumably is the adiabatic heating in the vicinity of the crack tip. This generally well known effect has been determined earlier with infrared cameras by e.g. Zehnder and Rosakis (1993) and has been measured in this investigation as well with a high-speed infrared camera of the latest generation. Since measurement of the temperature field is rather difficult with side grooves, for a basic investigation specimens were tested without side grooves at +20 °C and at a crack tip loading rate of $dK/dt = 3 \times 10^5$ MPa√m s$^{-1}$. ABAQUS-explicit has been used for the simulations of the SE(B)40/20 specimens without side grooves. Heat development due to work done in the plastic zone and heat conduction has been taken into account. Results of dynamic tensile tests in the range of strain rates between 0.004 s$^{-1}$ and 200 s$^{-1}$ served as basic input data, see Mayer (2015). An inverse simulation of the tensile tests, considering heat generation, heat conductivity and increasing local strain rate, was performed in order to obtain isothermal flow curves. Additional temperature dependent parameters such as the density, heat conductivity and specific heat of 22 NiMCr 3 7 has been used as further input data for the simulations. Future numerical simulations of specimens with and without side grooves shall be used as a reference to the here mainly tested specimens with side grooves.

The tests showed cleavage fracture with $K_{Jc,d(1T)}$ values of around 200 MPa√m at times-to-fracture of around 0.5 ms. At this instance, a comparison of the measured local strain field to the numerical calculated one shows very good agreement, as can be seen in Fig. 5.

The ductile crack extension of around $\Delta a_p \approx 0.15$ mm was neglected in the simulations. Therefore, measured strains very close to the vicinity of the crack tip are slightly overestimated by the simulation. However, at this location with a very high strain gradient the evaluation with ARAMIS starts to become invalid due to the limited spatial resolution of $L_{0,local} = 0.04$ mm.

The calculated and measured temperature field at a distance up to 0.75 mm around the crack tip also agrees quite well, see Fig. 6. Initial 3D simulations show an increase of $\Delta T \approx 60$ to 80 K at the specimen’s surface, which is close
to the measured maximum temperature increase of $\Delta T \approx 80$ K. Further evaluations and a more detailed analysis are considered in this investigation.

**5. Conclusions**

The determined fracture toughness values $K_{Jc,d}(T)$ decrease with increasing crack tip loading rate $dK/dt$ in the brittle to ductile regime, as expected. This is reflected by a shift of the Master Curve to higher temperatures, see Fig. 1. Thereby, the $K_{IR}$-curve represents the lower boundary curve for dynamic fracture toughness values. On the other hand, 5%-fractile curves of test series at test temperatures of -20 °C were in part below the $K_{IR}$-curve, see Fig. 1. Therefore, additional test series at two other temperatures (0 °C and +20 °C) and two loading rates ($dK/dt = 3 \times 10^3$ and $3 \times 10^5$ MPa√m s$^{-1}$) were performed and fracture toughness values and Master Curve reference temperatures $T_{0,x,single}$ according to the single- and multi-temperature evaluation were determined.

The results indicate a steeper course of the fracture toughness versus temperature curve. With an adjusted shape parameter $p$ of the Master Curve, this steeper curve could be well described with $p = 0.03$, as in Böhme et al. (2013). If the standard shape parameter of $p = 0.019$ is used the reference temperature $T_{0,x}$ is biased towards lower temperatures if the test temperature is higher than the reference temperature and vice versa if the test temperature is lower.

The steeper dynamic Master Curve is probably due to the effect of adiabatic heating in the vicinity of the crack tip. For the investigated testing conditions, the measurement of the temperature field around the crack tip on the specimen’s surface with a high-speed infrared camera resulted in an increase in temperature of around $\Delta T \approx 80$ K, which is in good agreement with the numerical simulation.

So far, the new appendix in the ASTM E1921 assumes the same shape of the Master Curve for quasistatic and dynamic loading. The here presented results for medium and high loading rates and at several test temperatures however show that the dynamic fracture toughness versus temperature curve $K_{Jc,d}(T)$ generally is steeper when compared to the quasistatic loading situation. This should be indicated in a future revision of the ASTM E1921 appendix for elevated loading rates. There, the possibility to adjust the Master Curve shape should also be considered. An explanation for this is founded in the effect of adiabatic heating.

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