

INSTRUMENTED IMPACT TESTING OF PRE-CRACKED CHARPY-TYPE SPECIMENS TO OBTAIN FRACTURE TOUGHNESS DATA FOR USE IN MASTER CURVE METHODOLOGY

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ABSTRACT

A method developed by the Swiss Federal Office for Materials Testing (EMPA), with support from the Swiss Federal Nuclear Safety Inspectorate (HSK), for testing pre-cracked Charpy-type (PCCT) specimens, has produced fracture toughness data. This has indicated applicability to nuclear power plant (NPP) surveillance specimens in the entire toughness range and allows failure assessment of components by application of Master Curve methodology in the lower transition regime, and by J-Integral methodology in the upper transition and upper shelf regime. Master curve methodology is seen as a promising option for assessing fitness for service of pressure vessel steel and for monitoring the effects of neutron embrittlement as fluence is accrued with operating time. Service-induced neutron embrittlement affects the temperature-pressurisation conditions for start-up/shutdown in a nuclear power plant, since the pressure vessel must not be pressurised whilst in a brittle state (i.e. at a temperature below which certain minimum fracture toughness is not existing). Current ASME Code reference toughness curves may be overly conservative. This could lead to unnecessary restrictions on pressure vessel operating life. Master Curve methodology potentially allows more flexibility in pressure-temperature limits and thus could contribute to pressure vessel life management whilst still assuring integrity and freedom from brittle fracture.

The PCCT test method includes an evaluation procedure to determine fracture toughness from a single force-displacement-diagram in the upper transition and upper shelf regions. Another issue dealt with in the method is the initial crack length, a_0 . The advantages of shorter cracks are discussed. The specimens used in the Swiss surveillance programmes have intentionally shorter cracks than the value of $a_0 = 0.5W$. The latter is, as theoretical investigation and experimental results reveal, not necessarily the best choice in dynamic testing of small specimens, anyway. However, shorter initial fatigue cracks (e.g. $a_0 = 0.3W$) need corrections due to relatively lower constraint. Furthermore, the size requirements of the specimens are often not fulfilled, and the loading velocity in testing is often higher than in service. Thus the transferability of the obtained toughness data from the PCCT specimen to large components is restricted. Simple functions to correct the measured fracture toughness data for these effects have been developed and are discussed in the paper.

KEY WORDS Instrumented Charpy testing, Pre-cracked Charpy, Master Curve methodology, pressure vessel fracture toughness, surveillance programmes and specimens, constraints, load-rate effects, size effects.

1. Introduction

Irradiation embrittlement is well known to affect mainly the brittle-to-ductile transition temperature (BDTT) and the magnitude of the upper shelf fracture toughness (Fig. 1). Fracture toughness is estimated from ΔRT_{NDT} and the $K_{IR}(T-\Delta RT_{NDT})$ -curve obtained from standard Charpy tests. Shortcomings associated with this practice have been identified and improvements proposed a long time ago [1],[2]. In particular, these are the assumptions underlying the indirect determination of the fracture toughness, and the non-existence of either well founded theoretical relations or reliable empirical correlation formulae of standard CVN test results to fracture mechanics parameters or the Pellini drop weight test. This is due to some fundamental differences between these tests: On one hand, the crack in a CVN specimen is only initiated after a considerable amount of material-dependent notch blunting and the corresponding strain hardening of the surrounding material, whereas in a fracture mechanics specimen the conditions for the onset of crack growth ("crack initiation") of a pre-existing (fatigue) crack are well defined. Besides, the notch depth of a CVN specimen does not represent the most unfavourable constraint conditions of a natural crack in a component. On the other hand, in the Pellini test, the crack arrest capability of the surrounding parent material is characterised, rather than the fracture initiation and propagation behaviour, as in the case of a CVN-test.

Fracture toughness testing of pre-cracked specimens is well suited to determine the dynamic fracture toughness transition curve (Fig. 1) and, thus to characterise ageing and irradiation effects. Therefore the irradiation surveillance program according to the concept of the Swiss Federal Nuclear Safety Inspectorate (HSK) as described in [1] also includes supplementary requirements for instrumented impact testing of pre-cracked Charpy-Type (PCCT) specimens (Fig. 2). The relatively new Swiss NPPs (Gösigen and Leibstadt) contain, in addition to the specimens according to ASTM E185, PCCT specimens [3]. The older NPPs, Beznau 1 and 2, and Mühleberg, do not have PCCT specimens in their standard surveillance programmes, but rest material from previous surveillance capsules may be used to reconstitute and create suitable specimens. The PCCT specimens should be tested by means of an instrumented pendulum hammer according to [4, 5]. However, there also are some problems to be handled. In the upper shelf regime the main one is that there still does not exist a generally accepted, adequately simple evaluation technique to obtain dynamic fracture toughness values, at least not as far as single specimen evaluation is concerned. Actually, there is no "exact" way of determining fracture toughness from a single load-displacement-diagram, as delivered from instrumented impact testing. Reproducibility and repeatability are essential features of tests performed within a surveillance programme. With these facts in mind, a suitable user-friendly evaluation method for PCCT specimens has been developed and implemented in [5]. Further details (apparatus, specimens, procedures, evaluation, test speeds, etc.) may be obtained from [5]. Basic ideas concerning the method are discussed in [6, 7, 8].

Efforts have been mainly concentrated on assessing the applicability of the evaluation method in the brittle-to-ductile transition regime, particularly in the lower transition regime, which is of prime importance in the surveillance of irradiation embrittlement. Here the direct evaluation of J_c or K_{Jc} values from impact tests of PCCT-specimens is

problematic, since the force signal is strongly affected by oscillations. In this regime, for $K_{Ic} < 100 \text{ MPa}\cdot\text{m}^{0.5}$, the master-curve [9, 10] can be used as an approximation. As shown in this paper, the single-specimen direct evaluation method, described in [5], can be applied for determining the fracture toughness in the upper shelf and upper transition range $K_{Ic} > 100 \text{ MPa}\cdot\text{m}^{0.5}$. Thus, it also can serve to determine directly the reference temperature T_0 that defines the master curve, valid in the lower transition range. These topics are addressed in the present paper.

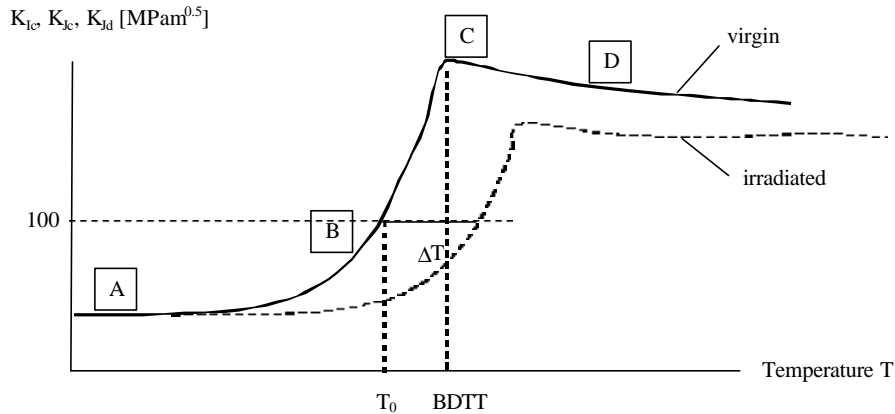


Fig. 1: Fracture toughness transition curve and effect of irradiation (schematic)

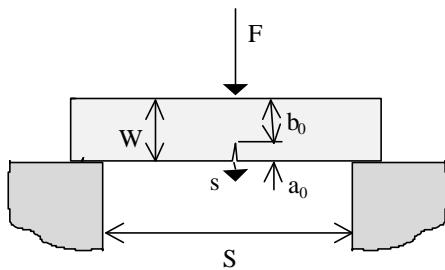


Fig. 2: Mechanical system of an impact test in three-point-bending (3PB)

2. Background

Reactor pressure vessel (RPV) surveillance specimen test programmes in nuclear power plants (NPPs) have the function to monitor the mechanical property behaviour of the RPV materials in the core beltline region of the RPV. These materials receive the highest fast ($E > 1 \text{ MeV}$) neutron fluence. Fast neutron fluence causes material degradation with time. This "neutron embrittlement", is measurable as a reduction in fracture toughness and ductility with a concurrent increase in material tensile yield stress and hardness as neutron fluence is accumulated over operational time.

The surveillance capsules, removed after various times of operation, lead the actual RPV materials (base material, welds, heat affected zones) in terms of fluence, usually

by a factor of 3 since they are nearer to the reactor core (e.g. behind the thermal shield (PWR) or attached to the inner wall (BWR) of the RPV) and thus are exposed to a higher neutron flux. Surveillance specimens (e.g. Charpy (CVN), pre-cracked Charpy (PCCT), wedge opening load (WOL), three point bend (TPB), tensile) can therefore be used to predict future RPV mechanical properties.

Assessment of RPV fracture toughness properties relies on evaluation of the behaviour of a material (weld, base, heat-affected zone) containing a sharp flaw, such as a crack, when put under load. The load may be static or suddenly applied, such as in the case of pressure transients or thermal shock during operation. The crack tip area may either tolerate the load and no crack propagation will take place or, if a material characteristic value of stress intensity factor (critical value of fracture toughness, K_{IC}) is exceeded at the crack tip, the crack could, theoretically, rapidly propagate, leading to RPV failure.

The "mainstay" (traditionally used) measures to assess toughness are the Charpy reference temperature of the nil-ductility transition temperature, RT_{NDT} and the upper shelf energy (USE). These parameters are defined in 10CFR50 Appendix G and Appendix G of the ASME Boiler and Pressure Vessel Code, Section XI. In common with many other NPPs world-wide, the Swiss NPP RPV surveillance programmes also depend, to a significant degree, on standard Charpy V-notch (CVN) specimen tests. This is due mainly to the ASME Pressure Vessel Code (manufacturing and material properties) requirements and therefore the focus is on the ASME Pressure Vessel Code Sections III and XI. These Sections are based on an approach that utilises a material normalising and indexing parameter, RT_{NDT} . This parameter is based on CVN results and drop weight nil-ductility transition temperature tests (Pellini) as defined in the Code. The RT_{NDT} is obtained, and the positions on the ASME K_{IC} (fracture toughness for static crack initiation) and the K_{IR} (fracture toughness for dynamic crack arrest) reference curves can be defined. The surveillance specimen's CVN-test shifts in transition temperature at the 41J (or, if required, 68J) energy level are progressively added to the RT_{NDT} value obtained for the unirradiated state throughout the RPV's life. The surveillance specimen temperature shifts are modified with margins to allow for uncertainties (fluence factor and chemistry factor) according to U.S. Nuclear Regulatory Guide 1.99, Revision 2. This method for estimating fracture toughness after irradiation relies on correlations to fracture toughness rather than direct measures of the property. Usually, the method underpredicts the real level of fracture toughness and this leads to a high level of conservatism (safety margin). This may impose unrealistic restrictions on the P-T limits of the RPV.

3. Evaluation of Dynamic Fracture Toughness

3.1. General Procedure

To evaluate fracture toughness values from force-displacement diagrams of instrumented tests on PCCT specimens (Fig. 3, Fig. 4), it is convenient to distinguish between the four ranges A – D defined in Fig. 1 and the corresponding diagram types shown schematically in Fig. 3. In principle, each type requires a special evaluation scheme. For

Types A and B, the J-Integral at initiation of unstable cleavage, J_u , is the characteristic fracture toughness value. It is obtained by:

$$J_u = \frac{h \cdot W_{up}}{B_N \cdot b_0} + \frac{(1-n^2) \cdot K_I^2(F_m, a_0)}{E} \quad (1)$$

where W_{up} is the dissipated energy at initiation of cleavage. Determining these required data by an instrumented impact test is difficult, since in this range the force-displacement diagram is usually strongly affected by oscillations, if the standard impact velocity of 5m/s is applied. In this range it is advisable to approximate K_{Ic} or its dynamic analogue K_{Id} , respectively, by the master-curve, which according to [9 – 11] is given by:

$$K_{Id} \cong 30 + 70 \cdot \exp(0.019 \cdot (T - T_{100})) \quad \text{for } T < T_0, 50\% \text{-failure probability} \quad (2a)$$

or

$$K_{Id} \cong 25.4 + 37.8 \cdot \exp(0.019 \cdot (T - T_{100})) \quad \text{for } T < T_0, 5\% \text{-failure probability} \quad (2b)$$

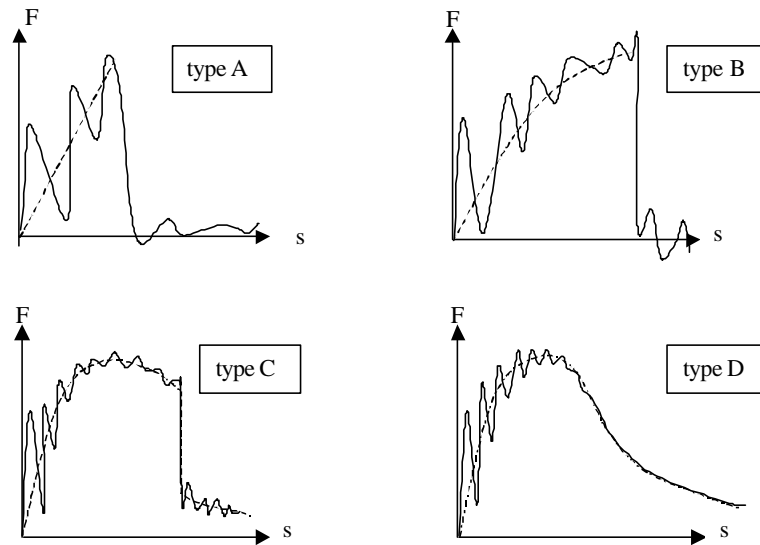


Fig. 3: Typical force-displacement diagrams (schematic, with different scales of s) and definition of toughness-range/diagram-types as follows:

Type A: Essentially elastic behaviour up to fracture

Type B: Initiation of cleavage fracture after some amount of plasticity, in the rising part of the F-s-diagram

Type C: Initiation of cleavage beyond maximum force (i.e. in the falling part of the F-s-diagram)

Type D: Fully ductile behaviour, no unstable cleavage

Thus, the toughness in the range $K_{Ic} < 100 \text{ MPa}\cdot\text{m}^{1/2}$ is fully defined by the reference temperature T_0 , which is the temperature corresponding to $K_{Ic} = 100 \text{ MPa}\cdot\text{m}^{1/2}$ (see Fig. 1). It is experimentally determined from a number of tests in the lower transition range, as prescribed in [11]. However, this procedure is problematic in the case of specimens as small as PCCT-specimens [12]. Therefore, we suggest to determine T_0 directly from test data in the upper shelf and upper transition range as shown below in section 3.2 and 3.3.

In the upper shelf range, the J-R-curve has to be evaluated from the force-displacement-diagram (Fig. 4) of a single impact test, since there are normally not enough specimens to apply multiple specimen techniques. Except for a draft of an ESIS guideline [13], no international standard exists for this purpose. In [5], the analytical approximation as derived in [7, 8], which also is part of [13], is suggested to be used for diagram types C and D. The procedure, which has proven to give reliable and repeatable results by several round robin exercises and comparison with multi-specimen J-R-curves [14], is outlined in the following section 3.2.

3.2. Upper Shelf and Upper Transition Range

In [7] and [8] a simple method to determine an approximate J-R-curve from a single force-displacement diagram, as obtained from a three point bending test, (Fig. 1), is presented. Since the theoretical derivation can be found in the above-mentioned references, we just give here the evaluation formulas. They are:

$$J(\Delta a) = C \cdot \Delta a^p \quad \text{for } \Delta a < (W - a_0)/10 \quad (3)$$

where

$$C = \left(\frac{2}{p}\right)^p \cdot \frac{h(a_0)}{B_N (W - a_0)^{1+p}} \cdot W_t^p \cdot W_{mp}^{1-p} \quad (3a)$$

$$p = \frac{2}{3} \cdot \left(1 + \frac{W_{mp}}{2W_t}\right)^{-1} \quad (3b)$$

and

$$h = 13.81 \cdot \frac{a_0}{W} - 25.12 \cdot \left(\frac{a_0}{W}\right)^2 \quad \text{for } 0 < a_0/W < 0.275 \quad (4a)$$

$$h = 1.90 + 0.143 \cdot \left(\frac{a_0}{W} - 0.30\right) \quad \text{for } 0.275 < a_0/W < 1 \quad (4b)$$

As can be seen from (1) to (4) the only required experimental data are – besides the geometrical parameters of the specimen such as initial crack length a_0 and the net thickness B_N - the energy consumed up to maximum force, W_{mp} , the total fracture energy W_t , and the maximum force, F_m (Fig. 4). These parameters can be easily and unambiguously extracted from the force-displacement-diagram delivered from the instrumented pendulum hammer, as indicated in Fig. 3. To minimise the effect of oscillations in the load signal, the impact velocity can be somewhat slower than the standard velocity of 5m/s.

The effect of a reduced speed has to be corrected for by an additional temperature shift as given in [6].

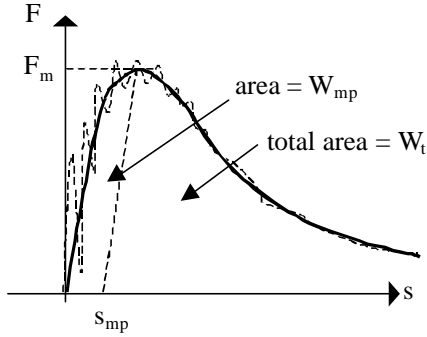


Fig. 4 : Schematic representation of the force-displacement-diagram and definition of the key-parameters W_{mp} , W_t and F_m

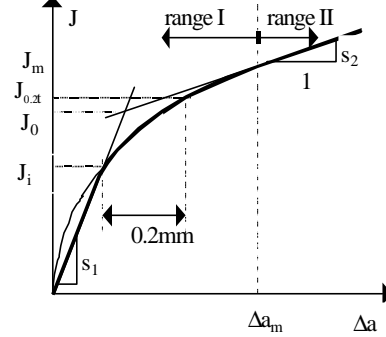


Fig. 5: J-R-curve and definition of the near-initiation J-values $J_{0.2t}$ and J_0

Having determined the J-R-curve, near-initiation fracture toughness values can be obtained analogously to quasi-static testing as standardised in [15] or [16]. However, it has been recognised before that because of the loss of constraints, small specimens tend to exhibit excessively steep J-R-curves and – correspondingly, too high values of $J_{0.2BI}$. For this reason we suggest to use $J_{0.2t}$ or J_0 as defined in Fig. 5 as more conservative alternatives. In mathematical terms they are obtained as follows:

$$J_{0.2t} = C \cdot \left[\left(\frac{C}{s_1} \right)^{1-p} + 0.2mm \right]^p + \frac{(1-n^2) \cdot K_I^2(F_m, a_0)}{E} \quad (5)$$

$$J_0 = (J_{mp} - s_2 \cdot \Delta a_m) \cdot \frac{s_1}{s_1 - s_2} + \frac{(1-n^2) \cdot K_I^2(F_m, a_0)}{E} \quad (6)$$

where C and p are given in (3a) and (3b), and

$$J_{mp} = \frac{h \cdot W_{mp}}{B_N \cdot b_0} ; \quad s_2 = \frac{2 \cdot h \cdot (W_t - W_{mp})}{B_N \cdot (b_0 - \Delta a_m)^2} ; \quad (7a)$$

$$\Delta a_m = \frac{A_g \cdot b_0 \cdot p}{2} \quad b_0 = W - a_0 \quad (7b)$$

$$s_1 = 3.0 \cdot s_{fd} ; \quad s_{fd} = \frac{F_m \cdot S}{B_N \cdot (W - a_0)^2} \quad (7c)$$

$$K_I(F, a) = \frac{0.92 \cdot F \cdot S}{(B \cdot B_N)^{1/2} \cdot (W - a)^{3/2}} \quad (7d)$$

By the well-known relation between J-integral and the stress intensity factor (SIF), K_I , one can transform $J_{0.2t}$ and J_0 , respectively, to obtain the dynamic fracture toughness values in terms of the SIF, i.e.

$$K_{J_{0.2t}} = (J_{0.2t} \cdot E / (1 - \nu^2))^{1/2} \quad (8a)$$

$$K_0 = (J_0 \cdot E / (1 - \nu^2))^{1/2} \quad (8b)$$

Which one of these two candidates of a fracture toughness value is preferable depends on the desired degree of conservatism. The smaller of the two may be chosen to be used in a fracture mechanics analysis. Which one is closer to the true value is one of the questions investigated in the following experimental part of the work.

3.3. Brittle-to Ductile Transition and Lower Shelf Regime

When dealing with structural problems, the most relevant fracture toughness range often is the lower transition regime, because it is here where brittle fracture is possible. In this range, the procedure shown in the above section is no longer valid since it applies only to the upper transition and upper-shelf regimes. However, the corresponding formulae (5) or (6) can be formally applied to the diagram types A, B and C, since the required input data W_{mp} and W_t still can be determined (although their physical meaning now is a different one). For type A, W_{mp} is equivalent to W_{up} which nearly vanishes, i.e. $W_{up} \approx 0$. One can see by inspection that (5) and (6) formally applied to type A and B diagrams deliver smaller values than (9). Thus, (8a) and (8b) are expected to deliver conservative fracture toughness values in the lower BDT-regime and the lower shelf. In case of type C diagrams, there is a J-R-curve similar as for type D, but for (5) and (6) to be applied, W_t should be scaled up to the value of a full ductile fracture. Obviously, (5) and (6) formally applied to type C diagram deliver lower-bound values. Thus, although (8) (or (5) and (6), respectively) have only a weak physical background in the BDT-regime, they can be formally applied in this regime to deliver conservative fracture toughness values.

Nevertheless, in the lower transition regime it is more suitable to use the master-curve (2). The value of T_0 , which fully defines the master-curve, is readily obtained by extrapolating the experimental K - data obtained in the upper transition regime by (8) and (5) or (6) down to $100 \text{ MPa}\cdot\text{m}^{0.5}$.

4. Experimental Considerations

4.1 Test Data

To assess the capability of the proposed method to give reliable fracture toughness data in the BDT-regime, a number of PCCT-specimens of a structural steel having similar properties as a typical RPV-material, were tested at the TVFA-Laboratory in Vienna [15, 16]. The test temperature range covered all the four diagram-types A through D as defined in Fig. 4. Only tests at 40°C showed purely ductile behaviour (Type D), allowing equations (5) and (6) to be applied.

The fracture toughness values derived using (8) with (5) and (6) are shown in Fig. 6. In this range, (8a) and (8b) are in good agreement with each other. Whether or not the results delivered by (8a) and (8b) in the BDT-range are still meaningful is considered in the following.

upper yield stress	lower yield stress	tensile strength	fracture strain	uniform fracture strain
R_{eH} [N/mm ²]	R_{eL} [N/mm ²]	R_m [N/mm ²]	A_5 [-]	A_g [-]
350	343	540	0.27	0.16

Table 1: Mechanical Properties of the test material

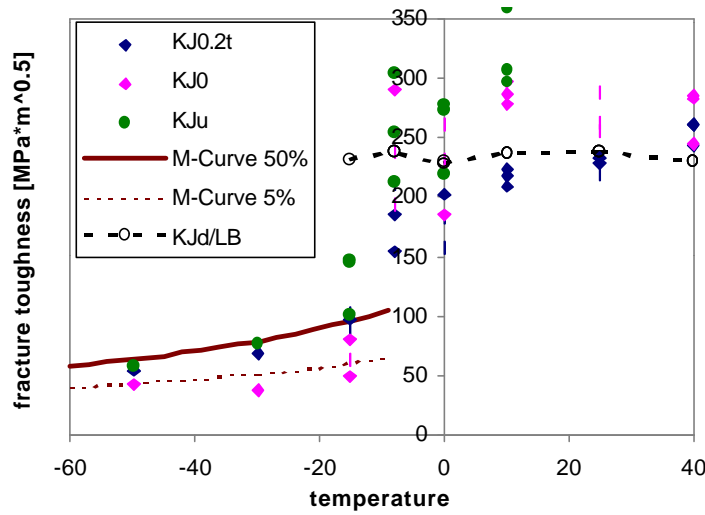


Fig. 6: Fracture toughness values evaluated by (8a) and (8b) as a function of temperature (in °C) in comparison with K_{Ju} and the master-curves (2a) and (2b).

4.2. Comparison with Cleavage Data

In Fig. 6, the results of (8a) and (8b) are compared with the SIF at initiation of cleavage, K_{Ju} , which is obtained by transforming J_u as given in (1) to a SIF by means of (8)). If the stable crack extension at initiation of cleavage, Δa_u , is smaller than about 0.3 mm, then the K_{Ju} values can be considered as near-initiation values in the upper BDT-range. As can be seen from Fig. 7, this is true for temperatures of 0°C and below. In this temperature range (i.e. $T \leq 0^\circ\text{C}$), the K_{Ju} -data can be regarded as "exact" reference values which can serve as a basis to assess the accuracy of the estimated values $K_{J0.2t}$ and K_{J0} . In Fig. 8, the J_u -values obtained by (1) are shown as a function of Δa_u , forming the so-called cleavage J-R-curve. These data are in good agreement with the J-R-curve calculated by means of (1) – (4) from the upper shelf data obtained at 40°C, confirming once

again the J-R- curve estimation procedure (1) – (4). The cleavage J-R-curve shown in Fig. 8 enables one to determine a reference upper shelf value of $J_{0,2t}$, which corresponds to about $K_{J_{0,2t}}=250 \text{ MPa}\cdot\text{m}^{1/2}$. This confirms the upper shelf data shown in Fig. 6. Moreover, in Fig. 7, the cleavage data are compared with the J-R-curve as obtained by (1) to (4) from the upper shelf test results at 40°C .

4.3. Comparison with Master-Curves

From the experimental points K_{J_0} and $K_{J_{0,2t}}$ next to $100 \text{ MPa}\cdot\text{m}^{0.5}$ the T_0 reference temperature, required to define the master-curve position, can be estimated. Since the drop of the experimental curves is rather steep in this region, T_0 is quite well defined, although the number of tests was relatively small. The $K_{J_{0,2t}}$ as well as the K_{J_0} –values indicate a value of about $T_0=-12^\circ\text{C}$. The K_{J_0} -values are higher in the upper shelf range and lower in the lower shelf, thus showing a sharper drop at the BDT-temperature. Thus, to determine the brittle-to-ductile transition temperature, J_0 seems to be somewhat better suited than $J_{0,2t}$.

The master curves given by (2) using $T_0 = -12^\circ\text{C}$ as described above, are shown in Fig. 6. For comparison the K_{J_0} and $K_{J_{0,2t}}$ – values obtained from (5) and (6), which according to the discussion in section 3.1 are expected to represent lower bounds, are also shown. Note that the master curve corresponding to 50% failure probability (eq. (2a)) is in good agreement with the $K_{J_{0,2t}}$ – values, whereas the one corresponding to 5% (eq. 2b) appears to agree better with the more conservative K_{J_0} .

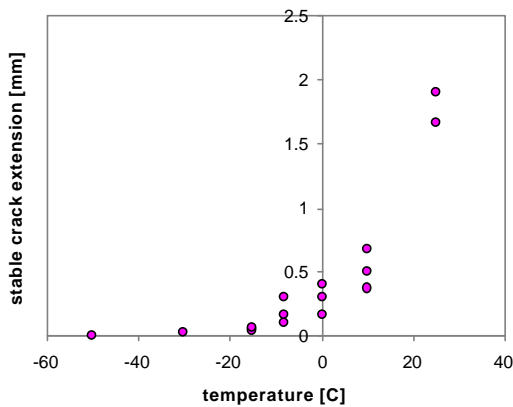


Fig. 7: Stable crack extension prior to cleavage initiation as a function of temperature

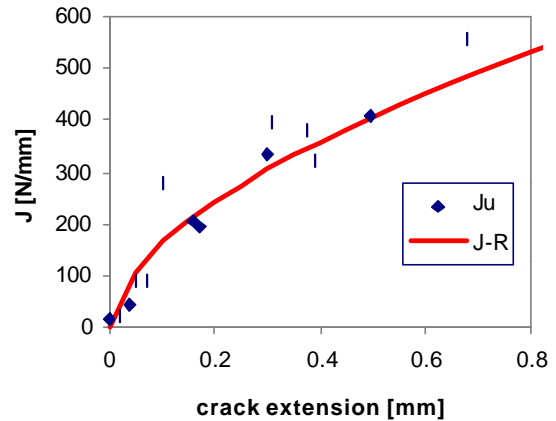


Fig. 8: J-values at initiation of cleavage, in comparison to the calculated J-R-curve from the upper shelf data (at 40°C)

4.4. Comparison with Compact Tension (CT)-Tests

For comparison, five 1T-CT-specimens made of the same material as the PCCT specimens were tested quasistatically [15]. Four specimens were loaded at room temperature to different levels of J or K_I . The corresponding stable crack propagation was measured

after breaking the specimens at -192°C . At -50°C a Type B behaviour was observed. A cleavage fracture was produced at $K_{\text{I}}=235 \text{ MPa}\cdot\text{m}^{0.5}$, after a stable crack extension of 0.178 mm. These data are shown in Fig. 9 as a K-R-curve, which is compared with the cleavage K-R-curve of the PCCT specimens obtained from the J-R-curve in Fig. 8 by using the transformation formula (8). The agreement is good, indicating that the PCCT specimens are able to provide fracture toughness data equivalent to those of larger CT specimens.

At -50°C a cleavage fracture was produced at $K_{\text{J}_0} = 235 \text{ MPa}\cdot\text{m}^{1/2}$. According to Fig. 6, this level of K_{J_0} or K_{J_u} is reached for the PCCT specimens at about -10°C . Thus, between dynamically loaded PCCT-specimens and statically loaded 1T-CT specimens, there is an observed shift of the BDT transition temperature of about 40°C .

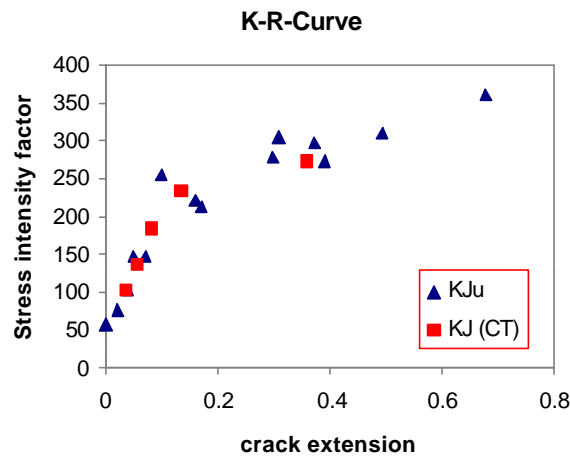


Fig. 9: Comparison of K_{J_u} -values at onset of cleavage with the K_{I} -values of the CT-specimens as a function of stable crack extension. (SIF $\text{MPa}\cdot\text{m}^{0.5}$, crack extension, mm.)

It is well known that an increased loading velocity causes a positive temperature shift (i.e. in the conservative direction), whereas the smaller size and the lower constraints of the PCCT specimens (compared to type 1T-CT) would result in a negative (non-conservative) temperature shift. The observed positive shift confirms that the velocity effect is dominant in PCCT-tests. Quantitatively, the temperature shift is material dependent. The observed 40°C holds only for the present testing material.

5. Some Remarks on Validity and Transferability

Critical J-values are only “valid”, (i.e. transferable to a fracture analysis of cracks in a larger structural part) if the specimen size meets certain minimum values given by the testing standards [17]. Adapting these criteria for quasistatic testing to the case of dynamic impact testing of PCCT specimens, the data evaluated by (5) or (6) are valid if :

$$J \leq D_{\text{J}_0} b_0/25 \quad \text{and} \quad J \leq D_{\text{J}_0} B/25 \quad (9)$$

For PC-specimens, where $b_0 < B$, the first of these criteria is decisive. If this is fulfilled, then K_{J_0} or $K_{\text{J}_0,2t}$ can be designated as a dynamic plane strain fracture toughness value,

K_{Jd} . If (5) or (6) do not fulfil (9), then a lower bound value of plane strain fracture toughness is given by:

$$K_{Jd/LB} = \sqrt{\frac{E \cdot \sigma_{fd} \cdot b_0}{Y(a/b) \cdot 25 \cdot (1 - \nu^2)}} \quad (10)$$

To remain on the conservative side, it is recommended to use $K_{Jd} = K_{Jd/LB}$ in a fracture mechanics analysis. For the tests reported in section 4, the corresponding lower bound value is shown as a nearly horizontal line in Fig. 6. In this case, the upper shelf values exceed this lower bound, so the latter has to be considered as fracture toughness for temperatures of about $T > 0^\circ\text{C}$.

Another topic needing attention is the initial crack length a_0 . Standard test specimens in static bending require an initial crack of a length of about $a_0/W = 0.5$ [17] to ensure maximum constraints. On the other hand, as discussed in [6], in impact testing of sub-sized specimens such as PCCT having a shorter crack length has several advantages concerning testing and evaluation, the main ones being:

- the shorter a_0 , the less restrictive is the condition for the validity of the resulting fracture toughness data (see eq. (12)).
- the shorter a_0 , the higher the force value in the force-displacement-diagram, and thus, the less it is affected by the inertial oscillations.
- the shorter a_0 , the closer is the shape of the ligament to the square shape of the ligament of a standard CT-specimen as is used in quasistatic testing.

Moreover, the size criteria often cannot be met, which means that the constraints are lower than in full size specimens anyway, and the data from PCCT-tests are often used rather for comparison than for a quantitative fracture mechanics analysis. For these reasons the specimens exposed to irradiation in the Swiss nuclear power-plants contain fatigue cracks of only about $a_0/W = 0.3$. An experimental investigation [18] did not exhibit a significant effect of the initial crack-length on the J-R-curve in the range $0.3 < a_0/W < 0.5$. A simple procedure to correct fracture toughness data for constraints is suggested in [19]. By applying it to the case of PCCT-specimens it was found that the maximum range of validity is obtained by $a_0/W = 0.3$ [20], which means that shallow cracks not only are beneficial concerning experimental effects, but also are of validity when applied in a structural analysis..

Concerning constraints and validity, side-grooving of the specimens may also have a positive effect. In the present investigation side-grooved specimens were used. From other comparisons, not shown here, we know that the J-R-curves are only little affected by side-grooves [18]. On the other hand we also know that side-grooving is beneficial with respect to straightness of the fatigue crack and conservatism of the evaluated toughness data especially in the BDT range. For these reasons, it is recommended to use side-grooved specimens whenever it is possible. It is rewarded from (13) by a higher lower-bound toughness $K_{Jd/LB}$ because of the higher dynamic flow stress as given by (7c).

6. Conclusions

The essential features of the evaluation method of PCCT tests proposed in [5], and presented here in section 2, are its straightforwardness, simplicity and clarity of interpretation. Since only well defined and easily obtainable experimental data are used therein, the proposed evaluation procedure is well suited for automatic computation, and the results are hardly affected by personal biases and engineering judgements. Concerning the range of validity and transferability it is advantageous to use specimens with a fatigue crack shorter than the standard $0.5W$, provided the reduced constraints are appropriately accounted for.

According to theoretical considerations, the evaluation procedure suggested in [5], which was derived for upper-shelf behaviour, can be applied in the brittle-to-ductile transition regime as well. In the upper transition regime, the near-initiation J_0 gives realistic, and $J_{0.2t}$ rather conservative fracture toughness data. This feature makes it particularly suitable to determine the reference temperature T_0 that defines the position of the master-curve along the temperature axis. For small specimens under dynamic loading this direct way of determining T_0 is preferable rather than the one corresponding to ASTM E1921.

In the lower transition range it is recommended that the master-curve should be used rather than directly measured fracture toughness values, because dynamic oscillations affect the accuracy of the measured data.

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