

Ageing and Irradiation Surveillance by Means of Impact Testing of Pre-Cracked Charpy Specimens

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Abstract: Instrumented impact tests using pre-cracked Charpy specimens offer several advantages concerning the physical significance of the test results as compared to the normally used standard Charpy-V-Notch tests. Therefore, this type of tests is included in the Swiss RPV-irradiation surveillance programme. However, since an international standard for the test evaluation still does not exist, these tests are more demanding in terms of expertise, testing and evaluation effort. To obtain reproducible and comparable fracture toughness data, it is essential that specimen preparation and raw data acquisition is well defined and standardized as far as possible. Particularly the evaluation of characteristic fracture toughness parameters should be as simple as possible and guarantee for unambiguous and repeatable results. For these reasons, a simple, user-friendly evaluation technique is included in the revised Swiss guideline for performing these tests. The present paper reports on some of the theoretical and experimental investigations that form the background of this guideline. It concentrates on the application of the method to determine fracture toughness values in the brittle-to-ductile transition temperature range.

1. Introduction

In the core beltline region of a nuclear reactor neutron irradiation is well known to cause material degradation with time. This phenomenon, called "neutron embrittlement", manifests in the loss of a certain amount of ductility and fracture toughness. Its progress is monitored by the so-called irradiation surveillance program (ISP), which, according to ASTM E 185, normally includes testing of irradiated Charpy-V-Notch (CVN) and tensile specimens that have been placed in capsules in the RPV. However, according to the present established practice, fracture toughness in the irradiated condition is not directly determined by fracture mechanics tests, but only indirectly by means of the "temperature-shift" (ΔRT_{NDT}) of the CVN transition temperature curves and the RT_{NDT} -concept (based on Pellini and CVN-tests) according to ASME Code Section III, Article NB 2331. The desired fracture toughness is estimated from ΔRT_{NDT} and the $K_{IR}(T-\Delta RT_{NDT})$ -curve as defined in the above-mentioned ASME code. Shortcomings associated with this practice have been identified and improvements proposed a long time ago (see Njo and Varga, Refs. [1] and [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.

There is no doubt that fracture toughness testing of pre-cracked specimens are best suited to determine and characterise ageing and irradiation effects. Therefore the Swiss ISP according to the concept of the Swiss Federal Nuclear Safety Inspectorate (HSK) as described in Ref. [1] includes supplementary instrumented impact testing of pre-cracked Charpy-Type (PCC) specimens. Consequently, the Swiss nuclear power plants (KKG and KKL) contain, in addition to the specimens according to ASTM E185, PCC specimens.[3]. The latter shall be tested by means of

an instrumented pendulum hammer according to [4]. However, there also are some problems to be handled. 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, so the results are necessarily approximations which usually are affected by personal judgements. Since reproducibility and repeatability are obviously essential features of tests performed within a surveillance program, a suitable, user-friendly evaluation method is included in the revised version of the testing guideline [5]. The basic ideas of this revision were discussed in [6].

After a short presentation of the evaluation method, in the present paper recent experimental work performed at TVFA, Vienna Institute of Technology [7] is presented and discussed. The aim was first of all to assess the applicability of the method in the brittle-to-ductile transition regime, which is of prime importance in surveillance of irradiation embrittlement.

2. Evaluation of Dynamic Fracture Toughness

In [8] and [9] a simple method to determine an approximate JR-curve from a single force-displacement-diagram as obtained from of a 3PB-impact test (Fig. 1) is presented. Since the theoretical derivation can be found in detail in the above-mentioned references, we just give here the evaluation formulas. They are as simple as follows:

$$J(\Delta a) = C \cdot \Delta a^p \quad \text{for } \Delta a < (W - a_0)/10 \quad (1)$$

where

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

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

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

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

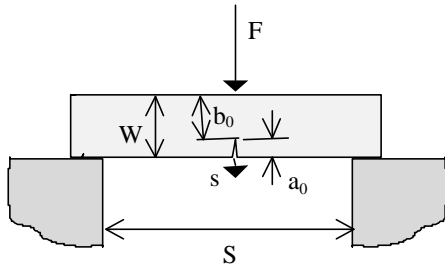


Fig. 1: Mechanical system of an impact test in three-point-bending (3PB)

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. 2). These parameters can be easily and unambiguously extracted from the force-displacement-diagram delivered from the instrumented pendulum hammer, as indicated in Fig. 2. 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 slightly reduced speed has to be corrected for by an additional temperature shift as given in [6].

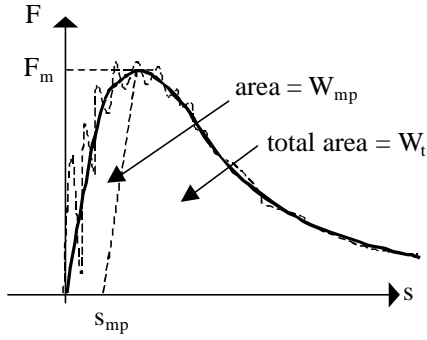


Fig. 2: Schematic representation of the force-displacement-diagram and definition of the key-parameters W_{mp} , W_t and F_m

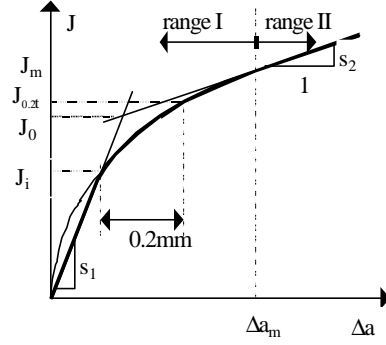


Fig. 3: J-R –curve and definition of the near-initiation J-values $J_{0.2t}$ and J_0

Once knowing the J-R-curve, near-initiation fracture toughness values such as the $J_{0.2BI}$ or the corresponding K_{Jc} can be obtained analogously to quasistatic testing as standardised in [10] or [11]. However, it has been recognised before that because of a loss of constraints small specimens tend to deliver too steep J-R-curves and – correspondingly, too high values of $J_{0.2BI}$. Therefore we suggest to use $J_{0.2t}$ or J_0 as defined in Fig. 3 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 (2) and (3), and

$$J_{mp} = \frac{h \cdot W_{mp}}{B_N \cdot b_0} ; \quad s_2 = \frac{2 \cdot h \cdot (W_t - W_{mp})}{B_N \cdot (b_0 - \Delta a_m)^2} ; \quad b_0 = W - a_0 \quad (7a)$$

$$\Delta a_m = \frac{A_g \cdot b_0 \cdot p}{2} \quad (A_g: \text{uniform fracture strain in uniaxial tension}) \quad (7b)$$

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

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

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.

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

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

Which one of these two candidates of a fracture toughness value is preferable depends on the desired degree of conservatism. In a fracture mechanics analysis, the smaller might be preferable for the sake of conservatism. Which one of the two is closer to the true value is one of the questions investigated in the following experimental part of the work.

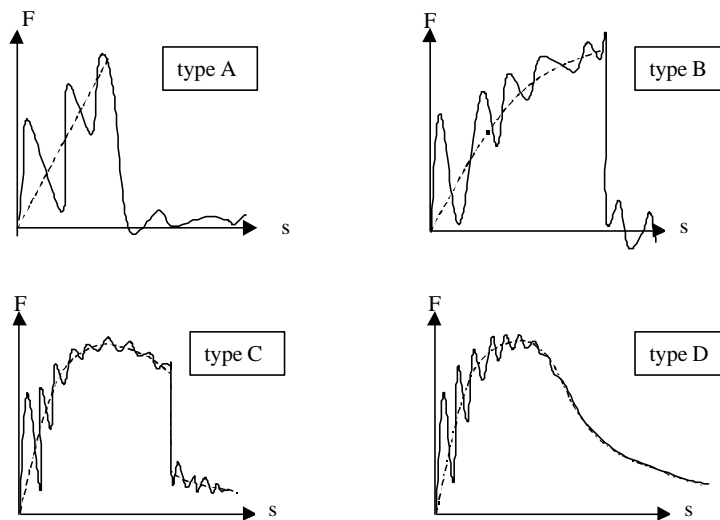


Fig. 4: Typical force-displacement diagrams (schematic, note different scales of s) and definition of toughness-range and corresponding diagram-types A, B, C and D as follows:

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

3. Fracture Toughness Evaluation in the Brittle-to Ductile Transition Regime

The formulas presented in the previous section are derived under the assumption of a full ductile tearing fracture, i.e. so-called upper shelf behaviour (Type D according to Fig. 4). In this regime they have been confirmed experimentally by several round robin exercises and comparison with multi-specimen J-R-curves (see eg. [11]). However, to identify effects of ageing or irradiation embrittlement, the brittle-to-ductile (BDT) transition regime is of main interest.

To evaluate fracture toughness values from force-displacement diagrams of instrumented tests on PCC-specimens it is suitable to distinguish between the four diagram types defined in Fig. 4. In principle, each behaviour requires a special evaluation scheme. For type A and B the J-

Integral at initiation of unstable cleavage, J_u , is the characteristic fracture toughness value. It is obtained by

$$J_u = \frac{h \cdot W_{up}}{B_N \cdot b_0} + \frac{(1-n^2) \cdot K_I^2(F_m, a_0)}{E} \quad (9)$$

where W_{up} is the dissipated energy at initiation of cleavage, i.e. it corresponds to W_{mp} for type B. For type A, W_{up} nearly vanishes, $W_{up} \approx 0$. 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. Thus, (5) and (6) formally applied to type C diagram deliver lower-bound values.

As a simpler alternative in the lower transition and the lower shelf range the so-called master curve according to [12] can be used instead of directly measured K_{Id} . For $T < T_{100}$ (where T_{100} denotes the temperature at which $K_{Id} = 100 \text{ MPa}\cdot\text{m}^{1/2}$) the fracture toughness (in $\text{MPa}\cdot\text{m}^{1/2}$) corresponding to a 50%-failure probability is given by the master-curve corresponding to a 5%-failure probability is given by

$$K_{Id} \cong 30 + 70 \cdot \exp(0.019 \cdot (T - T_{100})) \quad \text{for } T < T_{100} \quad (10a)$$

and the one corresponding to a 5%- failure probability by

$$K_{Id} \cong 25.4 + 37.8 \cdot \exp(0.019 \cdot (T - T_{100})) \quad \text{for } T < T_{100} \quad (10b)$$

As shown in [13], (10b) is nearly equivalent to the ASME lower-bound-curve [14].

4. Experimental Results

In order to assess the capability of the proposed method to give reliable fracture toughness data in the BDT-regime, a number of PCC-specimens of a structural steel that had similar properties as the RPV-material, were tested at the TVFA-Laboratory in Vienna. As allowed by [5], the impact velocity for all tests was chosen to be 2.5 m/s, since this reduction (in comparison with the standard velocity of about 5m/s) results in much lower oscillations in the load signal, but it does not shift the BDT-temperature significantly, just by about 5°C according to the estimation formula given in [6]. The mechanical relevant mechanical properties are given in Table 1.

upper yield stress	lower yield stress	tensile strength	fracture strain	uniform fracture strain
$R_{eH} [\text{N}/\text{mm}^2]$	$R_{p0.2} [\text{N}/\text{mm}^2]$	$R_m [\text{N}/\text{mm}^2]$	$A_5 [-]$	$A_g [-]$
350	343	540	0.27	0.16

Table 1: Mechanical Properties of the test material

In Fig. 5 the measured values of W_{mp} , W_t and F_m are shown as functions of the testing temperature. The fracture toughness values derived therefrom by using (8) with (5) and (6) are shown in Fig. 6. As indicated in Fig. 5 the tested temperature range covered all the four diagram-types A through D as defined in Fig. 4. Only the tests at 40°C behaved purely ductile (Type D) as in

principle required for (5) and (6) to be applied. In this range, (8a) and (8b) are in good agreement with each other. Their performance in the BDT-range is considered in the following.

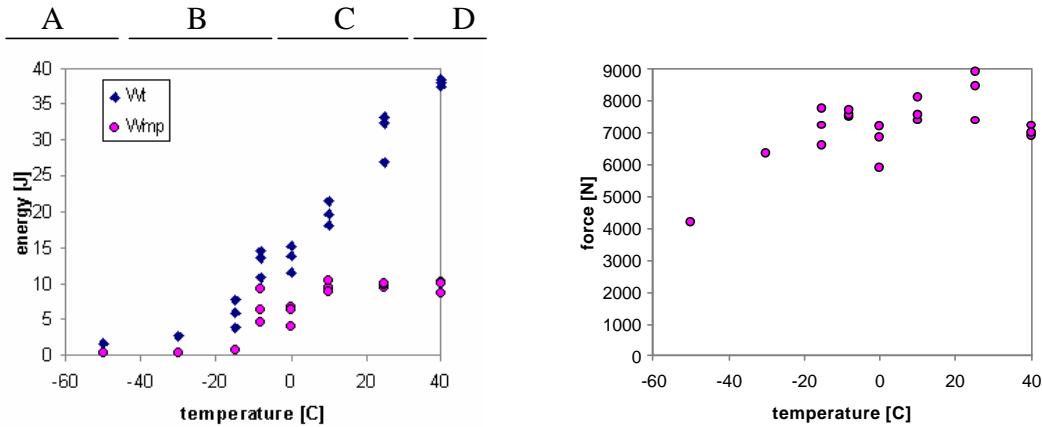


Fig. 5: Measured values of W_t , W_{mp} and diagram type (left) and F_m (right) as a function of temperature

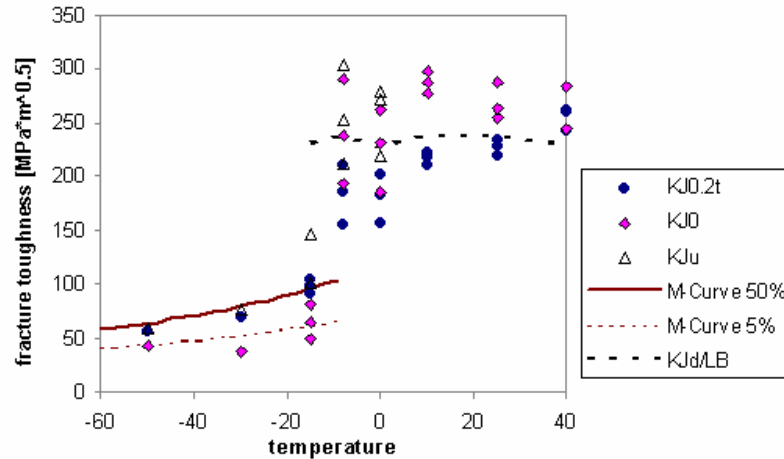


Fig. 6: Fracture toughness values evaluated by (8a) and (8b) in comparison with K_{Ju} and the master-curves (10a) and (10b).

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 (9) to a SIF by means of the relation analogous to (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} . Therefrom one can see that in the upper transition range K_{J0} are closer to the real fracture toughness values represented by K_{Ju} . Due to the sharp drop at the brittle-to ductile transition temperature they are best suited to define the BDT-temperature. The values $K_{J0.2t}$ tend to round off the transition from upper shelf to upper transition. Correspondingly the latter are more conservative in this regime.

In Fig. 8, the K_{Ju} -values are shown as a function of Δa_u , forming the so-called cleavage K-R-curve. From this cleavage K-R-curve one can estimate the reference upper shelf fracture toughness by the intersection with the 0.2mm-offsert blunting line to be about $K_{J0.2t} = 250 \text{ MPa}\cdot\text{m}^{1/2}$. This confirms the upper shelf data shown in Fig. 6 at 40°C, where upper shelf is reached.

In the lower transition and lower shelf (Type A and B according to Fig. 4) of Fig. 6 the experimental $K_{J0,2t}$ and K_{J0} data are compared with the master-curve approach, eqs. (10). The required value T_{100} was estimated from the $K_{J0,2t}$ values to be about -12°C . The 50%-failure probability curve (10a) is in good agreement with the $K_{J0,2t}$, whereas the more conservative K_{J0} rather seems to correspond rather to the 5%-failure probability curve (10b).

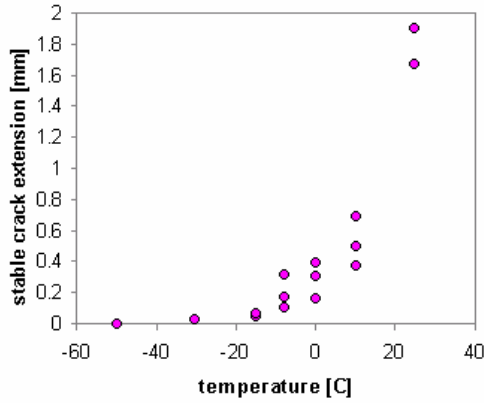


Fig. 7: Stable crack extension prior to cleavage initiation as a function of temperature

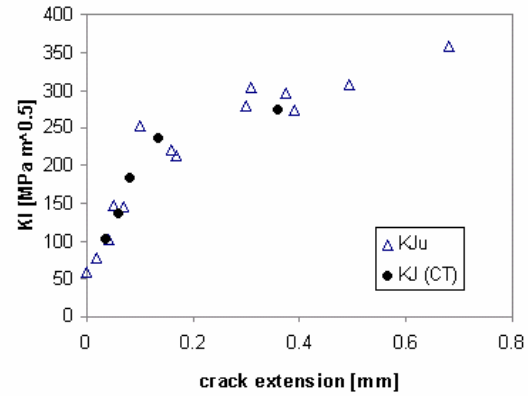


Fig. 8: Comparison of K_{Ju} -values at onset of cleavage with the K_I -values of the CT-specimens as a function of stable crack extension

4.2. Comparison with CT-Tests

To compare the data obtained from dynamic testing of sub-size specimens to the ones from quasistatic tests on standard specimens, five 1T-CT-specimens made of the same material as the PCC-specimens were tested quasistatically. 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 . These data are shown in Fig. 8 as a K-R-curve, which is compared with the cleavage K-R-curve of the PCC-specimens obtained from the J-R-curve in Fig. 8 by using the transformation formula (8). The agreement is very good, indicating that within the limit of validity the PCC-specimens are able to give toughness data that are comparable to those of larger CT-specimens.

It is well known that there is a temperature shift of the BDT. CT-specimens exhibited a Type B behaviour at -50° , where a cleavage fracture was produced at $K_I=235 \text{ MPa}\cdot\text{m}^{0.5}$, after a stable crack extension at of 0.178 mm. This point is also included in Fig. 8. According to Fig. 6, the level of $K_I=235 \text{ MPa}\cdot\text{m}^{0.5}$ is reached by K_{J0} or K_{Ju} , respectively, from the PCC-specimens at about -10°C . Thus, between dynamically loaded PCC-specimens and statically loaded 1T-CT-specimens, there is a shift of the BDT-transition temperature of about 40°C .

6. Conclusions

The present investigation showed that the presented evaluation procedure, which has been derived only for upper shelf behaviour, can be applied in the brittle-to-ductile transition regime as well. Summarizing, the following conclusions can be drawn:

- The fracture toughness values determined by (8) exhibit a lower scatter than the raw data raw data W_t , W_m and F_m .
- Both near-initiation parameters K_{J0} and $K_{J0,2t}$ are valid as approximations in the BDT-regime as well as in the lower shelf regime

- the K_{J0} -values are higher in the upper shelf range and lower in the lower shelf, thus exhibiting a sharper drop at the BDT-temperature.
- In the upper BDT-regime K_{J0} is closer to the true fracture toughness
- In the lower BDT-regime and lower shelf ($K_{Id} < 100 \text{ MPa m}^{1/2}$) (5) gives rather realistic, (6) rather conservative results.
- In the lower BDT-regime and lower shelf ($K_{Id} < 100 \text{ MPa m}^{1/2}$) the master-curve-approach can be used instead of direct test data
- The brittle to ductile transition is much better defined on the basis of SIF than of the total fracture energy.

The most noteworthy features of the evaluation method of PCC-tests suggested in [5] and roughly presented in this paper are its straightforwardness, simplicity and unambiguity. 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.

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