Some Issues by Using the Master Curve Concept

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ABSTRACT

The master curve concept allows to determine limit curves of fracture toughness for defined failure probabilities and a reference temperatures based on it. Thus fracture mechanical values can be supplied for the stress analysis. This paper presents the application of the master curve concept for the determination of the reference temperature over the thickness of a plate of RPV steel. It was shown that the master curve concept is applicable for the fracture mechanical characterisation of material in different conditions using small test specimens. A special problem with the use of small specimens is the definition of the test temperature, at which fracture toughness values can be determined within the validity limits. It became clear that the criteria for defining the test temperature and the minimum number of specimens indicated in the ASTM E1921-97 standard are applicable and sufficient respectively only for homogeneous materials.

1. INTRODUCTION

The state-of-the-art structural integrity assessment of reactor pressure vessels uses an universal and experimentally ensured fracture toughness reference curve, for example the American Society of Mechanical Engineers (ASME) K_{Ic} curve. This curve was constructed as the lower boundary to the available K_{Ic} database and, therefore, does not consider probability matters. The behaviour of a concerned material is considered by a reference temperature, the Nil-Ductility-Reference Temperature (RT_{NDT}). The shift of this temperature due to the irradiation and determined by Charpy-V impact tests reflects the irradiation-induced embrittlement (1, 2). This concept has the following disadvantages:

- it is not consistent since it links fracture mechanical and technological parameters and
- margins of safety and probability estimation cannot be quantified.

Moreover, a consistent evaluation after the plain-strain, linear-elastic concept is not really practicable because of specimen size requirements.

Recently, Wallin (3) has developed a new methodology to characterize the fracture toughness in the transition region. It uses J-integral-based cleavage fracture toughness values K_{Jc} . Wallin (3) has demonstrated that the probability-based estimates of the median fracture toughness of ferritic steels tend to form transition curves of the same shape, the so-called "master curve".

The mathematical functions of ASME and master curve are of the same shape. However, the

reference temperature, T_0 , for the temperature positioning of the master curve is evaluated by fracture toughness values determined from small specimens.

This report presents the application of the master curve concept to the fracture mechanical characterisation through the thickness of a reactor pressure vessel (RPV) segment from the IAEA reference material JRQ (A533B Cl. 1 RPV steel).

2. MASTER CURVE CONCEPT

For structural steels, a "master curve" describing the temperature dependence of the fracture toughness within the brittle to ductile transition region has been proposed by Wallin, that considers size effect and statistical variability in a simple way. While the ASME lower bound curve represents the minimum fracture toughness as a function of the temperature, the master curve represents the dependence of a median fracture toughness with temperature. The detailed description of the master curve approach can be found in (3,4,5). The statistical model developed by Wallin (3) suggests a 3-parameter Weibull distribution to characterise fracture toughness in the transition region. The cumulative failure probability P_f for failure at or before K_{JC} is described by:

$$P_f [K_{JC} \leq K_J] = 1 - \exp \left[- \left(\frac{K_{JC} - K_{\min}}{K_0 - K_{\min}} \right)^b \right] \quad (1)$$

where b is the Weibull modulus (shape factor),
 K_{JC} is the stress intensity factor,
 $K_{\min}$ is the lower limit of fracture toughness and
 K_0 is a temperature and specimen size dependent normalization factor.

Wallin (3) derived the theoretical value of 4 for the parameter b and 20 MPam^{1/2} for the minimum fracture toughness ($K_{\min}$). The only fitting parameter is the normalisation toughness K_0 . This parameter can be evaluated from a data set that at minimum consists of 6 valid fracture toughness values. A basic consequence of this model is the possibility to correlate fracture toughness values obtained from specimens of different sizes.

The master curve is described by the following equation:

$$K_{JC(\text{med})} = 30 + 70 \exp [0.019 (T - T_0)] \quad (2)$$

where $K_{JC(\text{med})}$ is the fracture toughness for a fracture probability of 50%,
 T is the test temperature of the data set and
 T_0 is the reference temperature at which the $K_{JC(\text{med})}$ value is equal 100 MPam^{1/2}.
 Thus, the reference temperature can be calculated by the conversion of the Eq. 3.

$$T_0 = T - \frac{1}{0,019} \ln \left[\frac{K_{JC(\text{med})} - 30}{70} \right] \quad (3)$$

This master curve is adopted in the ASTM standard procedure E 1921-97 (5) to present the median toughness behaviour in the transition region and its confidence intervals. The selection of the test temperature to obtain a sufficient number of valid K_{JC} values is a problem with the

application of the ASTM procedure E 1921-97 (5). It is recommended that the selected test temperature should be close to that at which the median K_{JC} value will be about $100 \text{ MPam}^{1/2}$ for the tested specimen. The maximum K_{JC} capacity of a specimen is given by:

$$K_{JC(limit)} = \sqrt{\frac{E b_0 \sigma_{ys}}{30}} \quad (4)$$

where E is the Young's modulus,
 σ_{ys} is the material yield strength at the test temperature and
 b_0 is the initial specimen ligament.

Such data that do not satisfying the requirement of Eq. 4 can be subjected to a censoring practice described in the ASTM standard E 1921-97 (5). However, at minimum 6 valid K_{JC} values measured at the same test temperature are recommended. At a lower shelf fracture toughness (K_{JC}) below $50 \text{ MPam}^{1/2}$ the statistical model is may be inaccurate (3). This shows the small area of validity of the measured fracture toughness values, in particular for small specimens. Charpy V-notch data, preferably in the T-L orientation, can be used as an aid to predict a viable test temperature according to the following relation (5):

$$T = T_{28J} + C \quad (5)$$

where T_{28J} is the temperature at which an impact energy of 28 J is achieved and
 C is a function of specimen size ($C = -50 \text{ K}$ for precracked and side grooved Charpy size specimens).

Wallin (3) suggests a multiple temperature (m-t) method, with which values which were determined at different temperatures, can be included into the reference temperature (T_0) evaluation. T_0 can be obtained iteratively from the following Eq.:

$$\sum_{i=1}^n \frac{\delta_i \cdot \exp(0,019 \cdot [T_i - T_0])}{11 + 77 \cdot \exp(0,019 \cdot [T_i - T_0])} - \sum_{i=1}^n \frac{(K_{Jc_i} - K_{min})^4 \cdot \exp(0,019 \cdot [T_i - T_0])}{(11 + 77 \cdot \exp(0,019 \cdot [T_i - T_0]))^5} = 0 \quad (6)$$

where the Kronecker's delta $\delta_i = 1$ when K_{JC} corresponds to failure by brittle fracture.

3. MATERIAL AND SPECIMENS

The material investigated is a rolled plate of the IAEA reference material JRQ (ASTM A533B Class 1 steel). The block with a thickness of 225 mm was cut into 20 layers over the thickness using an electroerosive cutting inachine. Table 1 contains the chemical composition and the mechanical properties.

The microstructure at various locations through the thickness was characterized by optical microscopy of etched metallographic sections. The basic microstructure is bainitic. The bainite is preferentially lower bainite and martensite at the surface layer and a heterogeneously composed upper bainite within the middle section. Reticular arrangements of martensitic structure occur within the bainitic basic structure. The reticularly arranged martensitic structure becomes more and more pronounced in the thickness direction and must be explained by segregation.

The following specimen types were tested:

- standard Charpy V-notched specimen (T-L orientation) and
- precracked and side grooved (20%) Charpy size specimens (T-L orientation).

4. TEST METHODS

The Charpy V impact tests were carried out with an instrumented 300 J impact-pendulum and at a test velocity of 5.5 m/s.

The fracture mechanical tests were performed according to the recommendations in the standard ASTM E 1921-97 (5). The specimens were loaded with a servohydraulic test system MTS 810 - Test Star using the unloading compliance technique. The measured J-integral values at brittle failure were transformed into elastic plastic stress intensities K_{JC} . The evaluation of the K_{JC} data of one test series were performed according to procedure of the ASTM E1921-97 (5) standard in the following sequence:

- Check of the measured K_{JC} whether they comply with the validity criteria of Eq. 4. K_{JC} values above the validity criterion were censored on the validity limit.
- Adjustment of the measured K_{JC} values on a specimen size 1T (width 25.5 mm). K_{JC} values below 50 MPam^{1/2} were not size adjusted.
- Calculation of the scale parameter, K_0 of the test series.
- Calculation of the median fracture toughness, $K_{JC(med)}$, of the test series.
- Calculation of the reference temperature T_0 . Additionally, T_0 was calculated according to the multiple temperature method using Eq. 6, including all valid and censored values.
- Calculation of the master curve and of the tolerance bounds.

5. RESULTS

The Charpy V-transition curves impact energy (KV), lateral expansion (LE) and percentage shear fracture (PSF) were evaluated by means of a hyperbolic tangent fitting procedure. Fig. 1 shows the dependence of the evaluated Charpy V- transition temperatures on the thickness. Obviously, the Charpy V- transition temperature increases from the surface to the middle. Strong scattering occurs, between the transition temperatures at different through thickness locations, especially within the middle range. There are no significant differences in the course of the scatter for the different Charpy V parameters (KV, LE and PSF). The scatter can be supposed to be connected with the reticularly arranged martensitic structure in the interior range of the plate.

The results of the reference temperature, T_0 , evaluation according to ASTM E1921-97 (5) and the multiple temperature procedure (3) are summarized in Tab. 2. So many specimens were tested from each thickness layer, as necessary to fulfil the recommendations of ASTM E1921-97 (5). The test temperature was determined by Eq. 6 using the T_{28J} transition temperature of the Charpy V results. However, it was not possible to get valid values for each thickness layer at this test temperature. For some thickness layers it was necessary to test at lower temperatures and to increase the number of tests. Test series of specimens from the interior range of the plate contain K_{JC} values above the validation limit of Eq. 5 and below 50 MPam^{1/2}. K_{JC} values above the validity limit of Eq. 5 were censored as suggested in ASTM E1921-97 (5). The censored values were included into the evaluation. For the additionally performed T_0 determination according to the multiple temperature procedure (Eq. 6) all tests which supplied valid or censored K_{JC} values were included. The influence of the test temperature is demonstrated in Tab. 2 for specimens from a thickness layer at 219.65 mm. At a test temperature of -130°C 3 K_{JC}

values above the validity limit (Eq. 4) were measured. These values were censored and included in the T_0 evaluation according to ASTM E1921-97 (5) for the test set at -130°C and the multiple temperature evaluation (Eq. 6). For the ASTM evaluation the number of valid values is not sufficient (minimum 6) at -130°C . In this case the calculated T_0 is lower compared to the test temperature of -140°C with only valid K_{JC} values. However, the multi temperature evaluation is also influenced by the censored values as shown in Tab. 2.

All elastic plastic K_{JC} data sets of the different thickness layers determined by the master curve concept according to the multiple temperature evaluation are shown in Fig. 2. The K_{JC} values are corrected at a specimen thickness of 25.4 mm (1T size). It is shown that most of the K_{JC} values are within the 5 and 95% tolerance bounds. K_{JC} values of specimens from the 1/4 to 3/4 through thickness position are outside the tolerance bounds. As already mentioned these K_{JC} values strongly scatter at the same test temperature. These results indicate that the statistical model on which the master curve is based on does not describe the cleavage fracture behaviour of a material with a structure, as it occurs in the interior range of the investigated RPV plate. Tab. 2 contains the values of the Weibull modulus, b , determined for the ASTM and the multiple temperature evaluation. The b values determined by K_{JC} values of specimens from layers up to 1/4 of thickness are closer at the assumed value of 4 than those of the interior range. The cleavage fracture behaviour of the bainitic structures with reticular arrangements of martensite is possibly not correspond to a Weibull distribution.

Fig. 3 shows the evaluated reference temperatures in dependence on the thickness position. In general, the course of the evaluated reference temperatures T_0 over the thickness is comparable with the Charpy V-transition temperatures. The scatter of T_0 is also especially high within the middle section of the plate.

Fig. 4 clarifies, that due to the scatter of the measured values there is no unambiguous correlation between the Charpy V transition temperatures and T_0 . At almost the same T_0 different Charpy V transition temperatures occur. This result underlines the difficulties with the definition of the test temperature of small specimens with a low fracture toughness measuring capacity.

6. CONCLUSIONS

The following conclusions can be made:

1. The master curve concept is applicable to the fracture mechanical characterisation of different materials using small test specimens.
2. A special problem with the use of small specimens is the definition of the test temperature at which fracture toughness values can be determined within the validity limits.
3. It is evident that the reliability of the master curve approach is restricted by the material quality. Inhomogeneous, segregated material results in large scattering in the measured fracture toughness values. In this case the supposed Weibull parameters are not valid.
4. The criteria to define the test temperature and the minimum number of specimens for the evaluation of the reference temperature T_0 as indicated in the ASTM 1921-97 (5) standard is applicable and sufficient only for homogeneous materials.

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TABLES

Table 1: Chemical composition (wt.%) and mechanical properties of IAEA JRQ RPV steel

C	Si	Mn	Cr	Mo	Ni	P	Cu	V	S	Al
0.18	0.24	1.42	0.12	0.51	0.84	0.02	0.14	0	0	0.02

tensile yield strength: 477 ± 10 MPa

ultimate tensile strength: 630 ± 3 MPa

Table 2 Results of the reference temperature (T_0) testing and evaluation according to the ASTM E 1921-97 (5) and the multiple temperature, m-t, procedure (3)

thickness [mm]	ASTM procedure						m-t procedure					
	T [°C]	N	N ^{*1}	N ^{*2}	$K_{Jc(med)1T}$ [MPa ^{1/2}]	T_0 [°C]	b	N	N ^{*1}	N ^{*2}	T_0 [°C]	b
5.35	-135	7	0	0	83	-120	3.6	15	2	0	-125	3.3
5.35	-120	7	2	0	113	-129	4.4	15	2	0	-125	3.3
15.85	-125	6	0	0	91	-118	2.8	11	0	0	-118	3.0
36.85	-100	6	0	0	88	-90	3.1	7	0	0	-93	3.1
50.10	-95	9	2	1	96	-92	1.9	10	2	2	-89	1.4
60.60	-94	15	0	3	70	-65	1.8	15	0	3	-65	1.8
81.60	-95	11	0	3	64	-57	2.1	11	0	3	-56	2.1
102.60	-75	7	1	0	91	-67	2.6	13	3	0	-66	2.8
113.10	-100	7	0	0	76	-78	4.0	15	3	0	-74	2.6
123.60	-75	15	3	1	95	-71	2.0	15	3	1	-69	2.0
144.60	-90	12	1	2	85	-78	1.7	15	1	2	-74	1.9
164.15	-95	7	0	0	75	-71	4.0	7	0	0	-70	4.0
174.65	-85	9	1	3	89	-76	1.3	15	3	3	-77	1.5
188.15	-100	6	0	0	86	-88	2.3	6	0	0	-90	2.3
209.15	-135	7	0	0	85	-122	3.1	7	0	0	-122	3.1
219.65	-130	7	3	0	123	-145	3.8	15	3	0	-134	3.2
219.65	-140	7	0	0	79	-122	5.2	15	3	0	-134	3.1

*1 number of tests with $K_{Jc} > K_{Jc(limit)}$

*2 number of tests with $K_{Jc} < 50 \text{ MPa}^{1/2}$

FIGURES

Fig. 1 Charpy V-transition temperatures versus distance from the surface

Fig. 2 Fracture toughness as determined with the master curve (m-t method)

Fig. 3 Reference temperature T_0 versus distance from the surface

Fig. 4 Reference temperature T_0 in dependence of the Charpy V transition temperatures