Application of the Master Curve Approach for Dynamically Loaded Pressure Vessel Steels

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ABSTRACT: *The master curve approach is a new concept for a fracture mechanics-based integrity assessment of pressurized engineering construction. It permits the determination of fracture toughness properties with small-size specimens under quasi-static loading conditions. The transfer of the quasi-static master curve approach to dynamical loading like Charpy impact testing would be expedient but is not trivial. In principle, the master curve approach seems to be applicable for dynamic loading. The detailed statistical analysis of the results, however, shows several shortcomings. The test temperature affects significantly the reference temperature, To. With small Charpy-size specimens valid values are only obtained if tested within the upper part of the lower shelf region. Approximately, the experimental results are compatible to the Weibull-distribution of the master curve concept.*

INTRODUCTION

The master curve (MC) approach developed by Wallin [1] suggests itself to be an excellent fracture mechanics based tool for brittle fracture safety evaluation of structural components. The master curve describes the temperature dependence of the J-integral related fracture toughness, K_{JC} on the base of a statistical brittle fracture model and using a reference temperature, T_0 for temperature scaling.

The material-dependent parameter T_o is defined as the transition temperature in °C where the mean fracture toughness of a 25 mm thick reference specimen is 100 MPa √m. The master curve is valid in the lower part of the ductile-brittle transition range. In this range the cleavage fracture is controlled by crack initiation but not by crack growth. The cleavage fracture can occur after a low amount of ductile crack growth.

The MC approach postulates the following assumptions:

- The fracture toughness, K_{Jc} can be described by a 3 parametric Weibull distribution

$$P\,[K_{Jc} < K_I] = 1 - \exp\left(\frac{K_{Jc} - K_{min}}{K_o - K_{min}}\right)^n \qquad (1)$$

with the parameters n = 4 and K_{min} = 20 MPa $\sqrt{m}$.

P (K_{Jc} < K_I) is the cumulative failure probability, K_{Jc} is the J-integral-related fracture toughness, K_o is a temperature and specimen size dependent normalisation fracture toughness corresponding to the 63.2 % cumulative failure probability.

- K_{Jc} value can be transferred to different specimen size by means of the Weibull distribution

$$K_{B2} = K_{\min} + [K_{B1} - K_{\min}]\,(\frac{B_1}{B_2})^{1/4} \tag{2}$$

B_1 and B_2 are the thickness of the specimens and K_{B2} and K_{B1} the corresponding values of the fracture toughness.

- The temperature dependence of K_o, related to B = 25 mm follows an exponential law

$$K_o = 31 + 77 \cdot exp\ [0{,}019\ (T - T_o)] \tag{3}$$

- The fracture behaviour is J integral related. This includes the maintenance of the constraint and it defines an upper limit of the validity of K_{Jc}

$$K_{Jc} \leq \sqrt{\frac{E \cdot b \cdot \sigma_y}{M\ (1-\upsilon^2)}} \tag{4}$$

with the Young`s modulus E, the thickness of the initial ligament b, the Poisson ratio ν, the yield strength σ_y and the size criterion constant M = 30.

On the base of a large data pool these assumptions could be proven to be well fulfilled for ferritic steels with yield stress of 255 - 825 MPa and for quasi-static loading condition. This has already led to standardization of appropriate tests.

Although the MC approach is applicable for both quasi-static as dynamic loading, the standards consider only quasi-static loading. However, in many cases of components integrity assessment problems of interest concern initiation of rapid crack growth due to dynamic loads. Thus, the extension of the MC approach to dynamic loading seems to be attractive, especially by using the Charpy impact test.

First papers have been shown the general applicability of the method under these circumstances [2]. However, there has been contradictory points of view to what extent the MC procedure must be modified. The following paper provides a contribution to this topic. For this purpose fracture mechanics impact tests with specimens of Charpy geometry from ASTM A 533 B cl.1 nuclear pressure vessel steel was performed and evaluated by the MC procedure. The dynamic reference temperature, T_o^{dyn} is compared with the quasi-static T_o^{stat} determined with the same specimen sets. These results are already published more detailed in [2]. This paper is focused on the statistical analysis of the results.

EXPERIMENTAL

The material used is a rolled plate of the IAEA reference material JRQ of the type ASTM A533B cl. 1. The material have been extensively characterized [3,4]. The plate of the thickness of 225 mm was cut into 20 layers over the thickness using an electro-erosive cutting machine. A total of 15 precracked and side grooved (20 %) specimens were machined from each layer in LT-orientation. The microstructure of the plate varies through the thickness. In the middle region heterogeneously composed upper bainite with segregation zones is characteristic.
The specimens were tested on an instrumented 300 J pendulum-type impact machine at a potential energy of 78 J and an impact velocity of 2.8 m/s. Test programme and evaluation were carried out in accordance to ASTM E 1921-97. The determination of T_o based on the multi-temperature procedure. In regard to a detailed description the reader is referred to [2].
A similar series of tests were performed using quasi-static 3-point bend loading condition and specimens of the identical geometry [5].

RESULTS

The scatter of the K_{Jc} values measured on specimens from the same depth position and at identical temperatures is large. Nevertheless, for each depth position a sufficient number of valid K_{Jc} for determination of T_o was available. Fig. 1 shows all experimental data (thickness corrected to 25 mm) independent of the validity according to ASTM E 1921. The results from the different layer locations are classified in two groups: surface near layers and layers between 1/4 and 3/4 of the thickness. Obviously, the experimental data do not closely follow the master curve. There are characteristic deviations in the lower and upper temperature range.

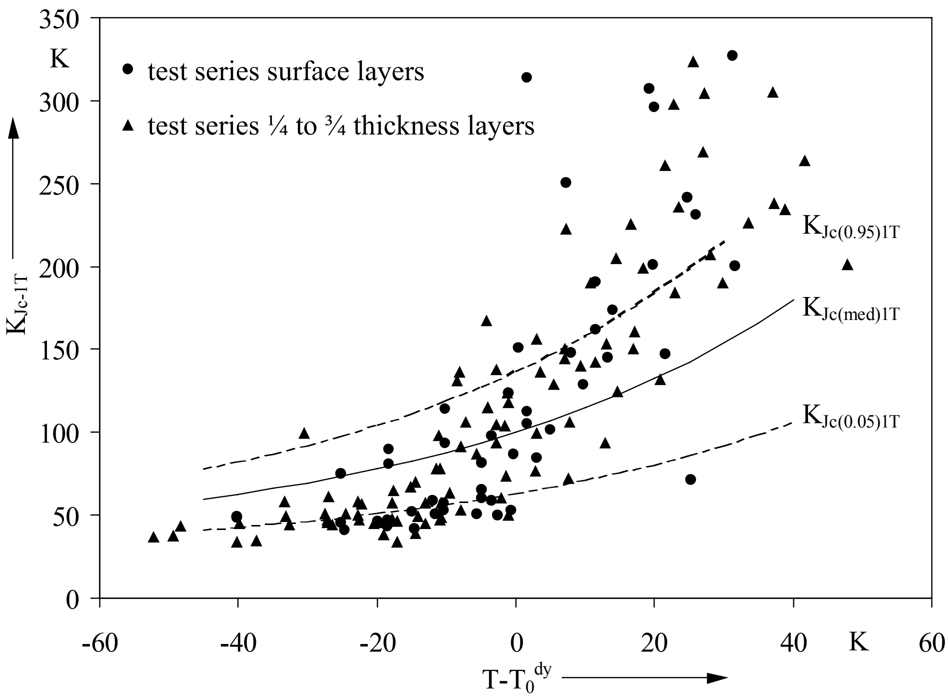

Fig. 1 Thickness corrected dynamic fracture toughness $K_{Jc\text{-}1T}$ for material investigated

The dependence of the ductile brittle transition temperature on the material depth is depicted in Fig. 2. In addition to the dynamically determined reference temperature, T_o^{dyn}, the static reference temperature, T_o^{stat} and the Charpy transition temperature, TT_{41J} related to an impact energy of 41 J are shown as well. All three parameters imply the same toughness gradient. It is steep to the surface whereas within the central portion between 1/4 and 3/4 of the thickness the level is constant. The correspondence of the three toughness parameters proves that the master curve concept is principally applicable for fracture mechanics characterization of the material behaviour under dynamic loading using small size test specimens.

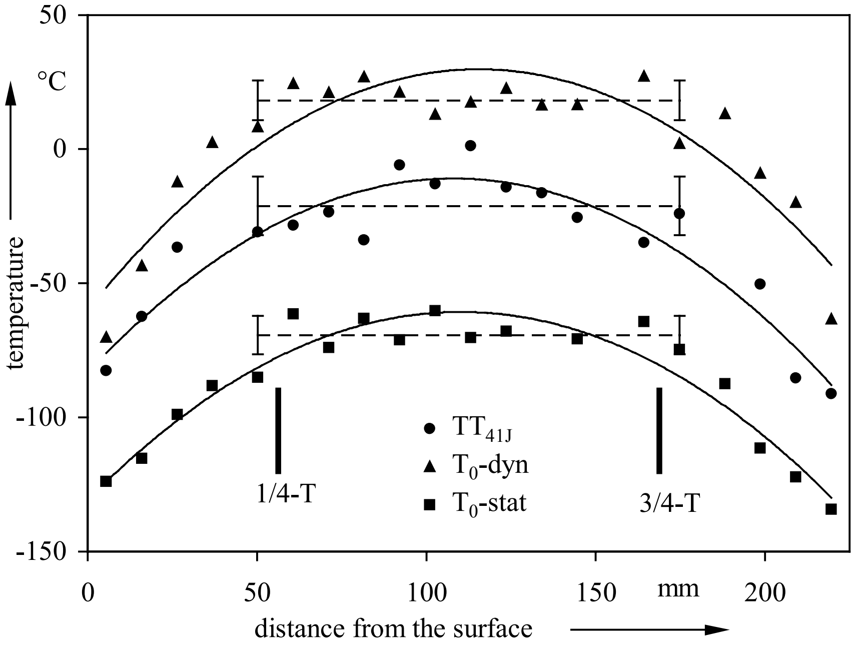

Fig. 2 Effect of specimen location on the ductile-brittle transition temperature determined by dynamic (T_o^{dyn}) and static (T_o^{stat}) master curve procedure and Charpy-V impact tests (TT_{41J})

STATISTICAL ANALYSIS

The influence of the depth position is not relevant for specimen locations between 1/4- and 3/4-thickness. Thus, the results are assumed to come from a material with identical but strongly scattering toughness from which a data set arises consisting of about 150 observations. This is a base for a statistical analysis to find appropriate fits and to perform hypothesis tests for various parameters and assumptions. For this purpose, the data were newly arranged in 10 subsets of isothermal series with 8 to 22 observations. The validation of the Weibull-Wallin distribution, the temperature dependence of T_o, and the accuracy of the T_o determination as function of the number of tests were tested. The statistical treatment used the Maximum-Likelihood-method and the Kolmogorov- Smirnov-test, mainly [6]. The same investigation was conducted for the static data set. This help to separate effects due to the material from the effects caused by the loading condition.

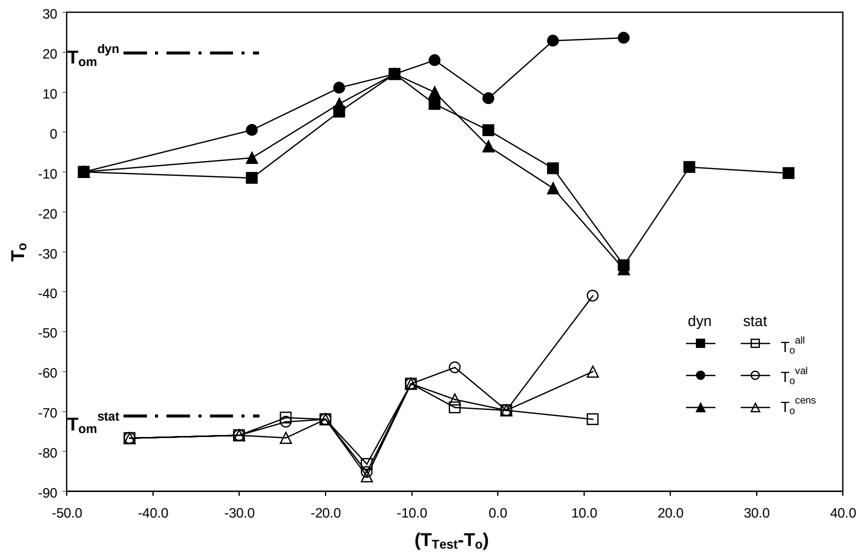

Fig. 3 Effect of the test temperature on T_o under static (T_o^{stat}) or dynamic (T_o^{dyn}) loading using all values measured (T^{all}), valid values (T^{val}) or valid and censored values (T^{cens})

The essential results are as follows:

1. Related to the valid K_{JC} values, there is a trend: The higher the test temperature the higher T_o (Fig. 3). Whereas the trend is within the scatter range of T_o for the original depth-related data sets for static loading, the trend is strongly significant for the impact tests and provides values of T_o far from the mean value. For test temperatures > T_o the measuring capacity (Eq. 4) is quite exhausted and the lost of constraint distorted the result.
2. The Kolmogorov-Smirnov test rejects the hypothesis, the experimental results are distributed according to Eq. 1 (Weibull-Wallin distribution) on the 5 % error probability level for the dynamic loading except both data sets with the lowest test temperature. For visualization the experimental results are shown together with the 95 % confidence bounds (calculated according to [6]) and compared with theoretical distribution for K_o calculated by Eq. 1 for the test temperature of 16.9 °C as an example. The theoretical distribution curve lies partly outside the confidence limit. This shows that the fixed Weibull parameters according to Wallin do not establish a good fit. Similar results are obtained at the other test temperatures. By contrast, the K_{Jc} values for

static loading provide better fits to the Wallin approach. However, even in this case there are data sets (4 of 9) for which the Kolmogorov-Smirnov test does not accept the Weibull-Wallin distribution.

3. Better fits can be obtained using K_{min} and n as additional free parameters of the K_{Jc} distribution. However, on average, the fit does not lie far from the Wallin-Weibull-distribution.
   For fixed n = 4, K_{min} scatters in the range of -18.5 up to 66.4 MPa√m at a mean value of 24.5 MPa√m if only taken the valid value or 18.5 MPa√m under consideration of the censoring procedure. On the other hand, assuming K_{min} = 20 MPa√m, the parameter n varies from o.74 up to 6.15 and has an average of 4.56 for the valid data or 4.49 with censoring.
4. Using small specimens of Charpy geometry, valid test series for T_o determinations are only obtained from tests at temperatures < T_o. Comparing the dependence of the fracture toughness on the temperature as shown in Fig. 5, this means that the transition temperature criterion T_o is rather predicted in the upper part of the lower shelf range than in the low- to mid-transition. Within this range the fracture toughness weakly depends on the temperature and, thus, the accuracy of the T_o determination is substantially reduced. Basically, there is no difference between dynamic and static loading regarding this trend.
5. Despite of the high material-caused scatter and the unfavourable measuring condition, the recommended minimal sample size of 6 valid tests is sufficient for the determination of T_o within the theoretically expected average standard deviation $\sigma(T_o) = 17/\sqrt{n}$ [1] . For example, a sample of 18 valid tests at T_{Test}= 10.5 °C provides T_o = 14.4 ± 4.0 °C. 20 random-selected subsamples of 6 tests from the sample result in T_0 values between 9.6 °C and 22.6 °C with a mean value T_o = 15.0 ± 4.2 °C. Only for two values the mean value is not covered by their theoretical standard deviation of 6.9 °C. However, this is only valid for a quite small range of test temperature near (but lower than) the reference temperature, T_o.
6. Altogether, the results encourage to define more strictly the procedure for the T_o determination rather than to reject the Wallin-MC approach and formalism in the case of application for dynamic loading.

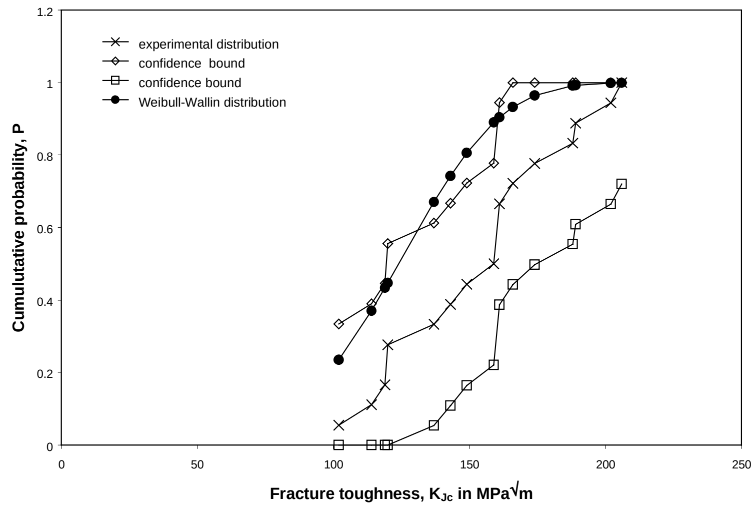

Fig. 4 Comparison of the experimental distribution and the Weibull-Wallin distribution for T_{Test} = 16,9 °C, dynamic loading

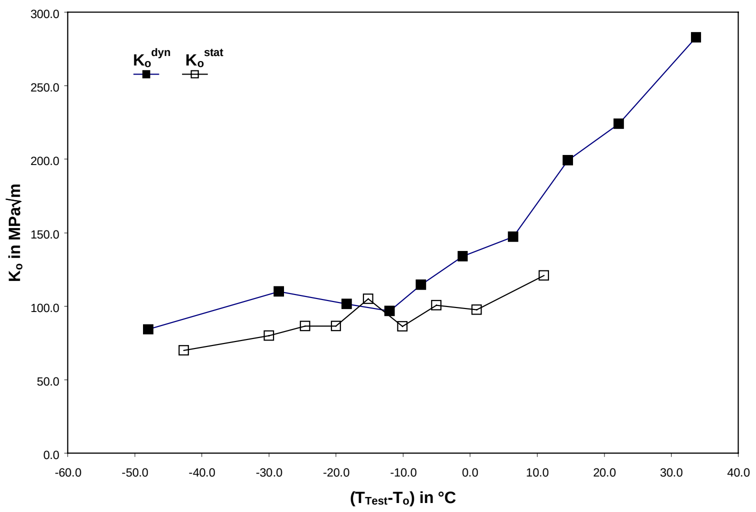

Fig. 5 Temperature dependence of the Weibull distribution normalization fracture toughness, K_o for dynamic and static loading

REFERENCES

1. Wallin, K. (1999) *Int. J. of Materials and Product Technology* **14** 342.
2. Viehrig, H.-W., Böhmert, J. *Use of Instrumented Charpy Impact Tests for the Determination of Dynamic Fracture Toughness Values,* ESIS, Charpy Centenary Conference - CCC 2001, 3-5 October 2001, Poitiers, France, publ. forthcoming.
3. Ando, Y. (1986) *Manufacturing History and Mechanical Properties of Japanese Materials Provided for the International Atomic Energy Agency,* Atomic Energy Research Committee, Japan Welding Energy Society, CRP subcommittee report.
4. Wallin, K., Valo, M., Rintamaa, R., Törrönen, K., Ahlstrand, R. (1989) Research Report 639, Technical Research Centre of Finland, Espoo.
5. Viehrig, H.-W., Böhmert, J. *Some Issues Using the Master Curve Concept* (1999). In: Proc. Of the 15th Intern. Conf. On Structural Mechanics in Reactor Technology, SMIRT-15, Chang, S. P. (Eds.). Seoul, Korea, Vol G 10/1.
6. Norman, L. J., Leone, F. C. (1977) *Statistics and Experimental Design in Engineering and the Physical Sciences*. John Willey & Sons, New York.