Master curve evaluation at static and dynamic conditions of loading for cast ferritic steel

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ABSTRACT

The methodology of master curve (MC) has been applied for assessment of the fracture toughness transition behaviour of cast ferritic steel. Low carbon manganese steel intended for fabrication of large containers of spent nuclear fuel (SKODA) was used for the analysis. Two locations, surface layer and central part, of the thick-walled plate have been followed in order to evaluate the material fracture resistance of full-scale cask segment. For determining the reference temperature T_0, that is taken as a basic material characteristic positioning the MC on the temperature axis the standard (1T) bend specimens were taken. Fracture toughness data were determined for two different loading rates. For dynamic loading two calculation procedures of dynamic fracture toughness determination have been applied, the first one arising from quasistatic approach and the other based on concept of dynamic key curve method. The shift of reference temperature for dynamic loading toward to higher temperature when relating to static loading was evaluated. Additionally, the pre-cracked Charpy type specimens have been also used for determining the fracture toughness transition behaviour. Similar strain rates have been applied for these specimens as in case of 1T specimens. The transferability of results received on the small pre-cracked Charpy specimens was analysed and applied with good results. Based on recent knowledge in the field concerned the standard and pre-cracked CVN specimens have been assessed and micromechanical aspects of steel fracture resistance were analysed.

INTRODUCTION

The assessment methods of fracture mechanics have increased to a point where certain structural materials, until now not considered for radioactive transport and storage casks design, are being proposed for these applications [1]. As example, the cask design based on thick-walled cask with bolted lids, both fabricated from cast low carbon manganese steel with ferritic microstructure was introduced by producer SKODA Nuclear Machinery.

For the safe enclosure of the radioactive material during transportation it must be proved that the extension of non-detected cracks after fabrication will not occur even in case of most severe accident loading [2,3]. For safe storage additional embrittling effects should be taken into account. Brittle fracture can occur under specific combination of temperature, mechanical and environmental loading. Several approaches might be applied or developed in order to solve the problem of the container integrity from the point of view of material fracture resistance assessment and prediction. These include local approach [4-6], toughness scaling models [7,8 etc.] and master curve methodology [9-12 etc]. The capability to predict the fracture behaviour for any configuration of defect and component could be taken as a very hard criterion of such procedure.

The methodology of master curve (MC) [9] is currently widely used for assessment of fracture toughness transition behaviour. The verification of this concept has been performed for pressure vessel steel [10,12-18]. For determining the reference transition temperature, T_0 that is taken as a basic material characteristic localising the MC on the temperature axis the large (1T) specimens are required. But there are structures under operation for which the transition behaviour of fracture toughness is of great interest (reactor pressure vessels, rotors etc.) and application of MC concept would be very useful. For these components only small specimens (pre-cracked Charpy type - PCVN) can be used for assessment of degradation, however. It has been shown [10,18] that the PCVN specimens can be used in determining the reference temperature and thereby making possible to apply MC concept for the integrity assessment procedure of these components.

As proved by Dodds, Anderson and Nevalainen [19-21] the PCVN specimens lose constraint well before the onset of unstable fracture. The results obtained provide very unconservative and invalid estimate of conditions required for the onset of unstable fracture in full-scale component. It has been found however, that if the PCVN specimens were loaded in impact the additional constraint would be present at the crack tip allowing to predict correctly the unstable fracture initiation from the PCVN data [10]. This allows the factor in the size-deformation limit to be reduced from the range of 50 to 100 to between 25 and 30 and the PCVN results to be qualified for prediction of unstable fracture initiation in 1T specimens or full-scale components [22].

Based on 3D calculations and toughness scaling model [19,20] the PCVN data not meeting the size-deformation limit (i.e. toughness data in constraint dependent regime) may be adjusted and used for fracture toughness prediction in transition region. The fracture toughness values determined by using PCVN specimens, size corrected according to standard [9] and adjusted for constraint effect, provided good prediction, fully comparable to real 1T data [23].

The aim of the present contribution is to characterise the fracture resistance applying the master curve methodology of cast ferritic steel predetermined for radwaste casks. The special attention should be paid to the application of this methodology for data obtained at dynamic conditions of loading. Additionally, the prediction of the fracture toughness scatter of large (1T) specimens from small pre-cracked Charpy ones tested dynamically has been also performed.

EXPERIMENTAL DETAILS

Material Characterisation

Manganese cast steel has been used having the following chemical composition in wt %: 0.09C, 1.18Mn, 0.37Si, 0.01P, 0.025S, 0.12Cr, 0.29Ni, 0.29Cu, 0.03Mo, and 0.028Al. The material has been obtained in form of 270 mm thick plate produced as a segment of full-scale container cask in the frame of metallurgical technology development. Special heat treatment based on intercritical austenitisation was developed in order to produce homogeneous properties throughout the plate thickness [24]. Two location have been followed namely the central part (C) and surface layer (E) of thick-walled plate.

True stress-strain curves have been determined using cylindrical specimens with a diameter of 6 mm in the temperature range -196°C to -60°C at a crosshead speed of 2 mm.min^{-1}.

The cast steel examined exhibits relatively low values of lower and upper yield stress and with decreasing temperature these characteristics increase very slowly (E.g. at –100 °C the yield stress is equal to 420 MPa for location C and 455 for location E). With respect to small pre-cracked specimens this fact resulted in the necessity to carry out the static tests of PCVN specimens at very low temperatures in order to fulfil the criteria for the determination of valid K_{Jc} values.

Mechanical Testing and Calculations

For fracture toughness determination, both for the static and dynamic loading, two test specimen configurations have been used: The standard one (1T, i.e. 25 and/or 23 mm thick specimens) and the small pre-cracked CVN specimens.

In case of standard fracture toughness determination and static testing the three-point bend (1T SENB) specimens 25x50x220 mm^3 have been used. These specimens were tested at 1mm/min crosshead speed in the temperature range from –198 to –20 °C. Two sets of specimens have been tested at selected temperatures (at –120 °C and –90 °C for location C; at –130 °C and –100 °C for location E) in transition region close to lower shelf in order to follow the statistical aspects and another one close to upper shelf. The fracture toughness values have been determined according to ASTM E 1820-99a.

The modified geometry of test specimens was used for dynamic fracture toughness determination. The dimensions 23x23x110 mm^3 have been adjusted to maximum possibilities limited by geometrical dimensions of fixtures on drop weight tower [26]. These specimens were tested at drop weight velocities of 1.99 ms^{-1} to 3.00 ms^{-1} in the temperature range from -50 to -10 °C. The dynamic fracture toughness values have been determined by two procedures. The first one was based on standard approach as used for static conditions of testing. The only difference was the careful reading of unstable (fracture) load and necessity to apply smoothed traces before the determination of plastic work to fracture. The other method was based on dynamic key curve [27], a method that is predetermined for high strain rate loading. The results of both assessment procedures have been compared and applied for master curve evaluation.

Small pre-cracked Charpy type specimens (PCVN) have been tested statically and dynamically. For the last the low blow method applied on instrumented impact tester (loading rate of about 1 ms^{-1}, similar strain rate as in case of large specimens) was used to generate the necessary data over needed temperature range.

For master curve analysis standardised approach was applied according to standard ASTM E 1921 –97 [9]. The standard FEM code ABAQUS 5.7 was used to model elastic-plastic behaviour (almost in 3D) for all test specimen geometries investigated. Extensive fractographic observations have been carried out in order to investigate the micromechanistic aspects of unstable fracture initiation. More detailed analyses are available recently in [25] and will be published later [22].

RESULTS AND DISCUSSIONS

Fracture Behaviour of 1T SENB Specimens

For static loading and standard geometry of test specimens the fracture toughness temperature diagrams are shown in Fig. 1 for central part of the plate (location C) and in Fig. 2 for surface layers (location E). There are all typical areas in the transition and lower shelf region. The empty points represent the K_{Jc} values obtained in elastic plastic regime without any ductile tearing; the filled points represent K_{Ju} - fracture toughness data with ductile growth higher than 0.2 mm. Some data characterising the fully ductile fracture are also displayed in the figures.

For further consideration the K_{Jc} values fulfilling the validity condition are important. For the size-deformation validity conditions shown in figures the following equation was used:

$$K_{Jc(\mathrm{limit})} = [(E b R_e)/50]^{1/2} \tag{1}$$

This equation is represented by the full thin curve in both Figures 1 and 2. The value of constant in Eq. (1) was taken to be 50 instead of 30 in the standard [9] based on work of Ruggieri et al [7].

Data K_{JQ} lying above the limit curve represent failures in the constraint dependent regime ($Q \neq 0$), are invalid and without any adjustment cannot be used for further fracture resistance assessment. Corrections could be introduced, however, for these data, e.g. by using toughness scaling models [19,20]; such approach has been discussed in work [23] as example. For simplicity, the data lying above the limit curve will be rejected from the following considerations in this investigation.

Exponential fit has been calculated for all the fracture toughness values lying under the validity limit. The mean fracture values, $K_{Jc(mean)}$, are identical fully to $K_{JC\,(med)}$ curve for C (Fig. 1) and/or are represented by thin dashed line in Fig. 2.

Based on the K_{Jc} values meeting the validity limit the reference temperature T_0 was determined. All the K_{Jc} results obtained have been checked whether the basic assumption included in ASTM Standard E1921 [9] for determining the reference temperature T_0 was met, i.e. whether the cast steel tested obeys the three parametric Weibull distribution with the Weibull modulus m equal to 4. Applying the maximum likelihood method, suggested by Wallin [18] for evaluation of toughness data obtained at different temperatures*), the reference temperature was determined to be T_0 = -126.2 °C for location C and T_0 = -143.8 °C for location E (see also Table 1). The master curve for the C-Mn cast ferritic steel – in the central part (location C) can thus be described by the equation:

$$K_{Jc(med)} = 30 + 70\exp[0.019(T + 126.2)] \tag{2}$$

For the surface parts of thick walled plate (location E) the master curve can be described by the equation:

$$K_{Jc(med)} = 30 + 70\exp[0.019(T + 143.8)] \tag{3}$$

In Figures 1and 2 the master curves together with the 5% and 95% probability scatter bounds are displayed. It is evident from the figures that all experimental values fall well to the scatter band. As mentioned for location C the master curve ($K_{Jc(med)}$) obtained corresponds well to the exponential fit ($K_{Jc(mean)}$) calculated from the valid K_{Jc} data.

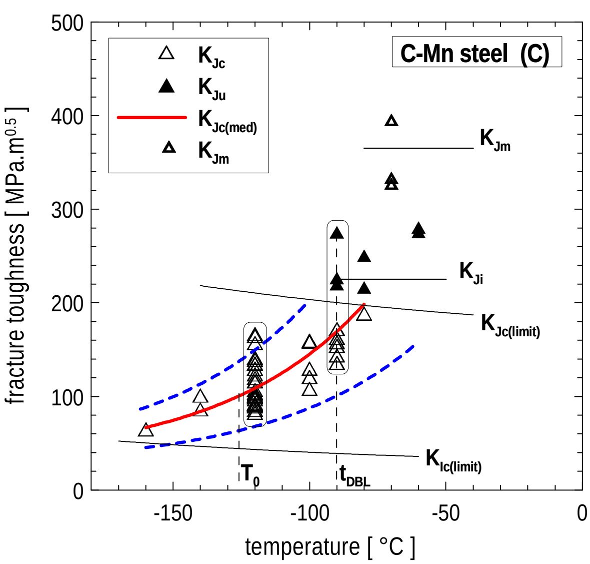

Fig. 1 Fracture toughness temperature diagram for central part of the plate (location C)

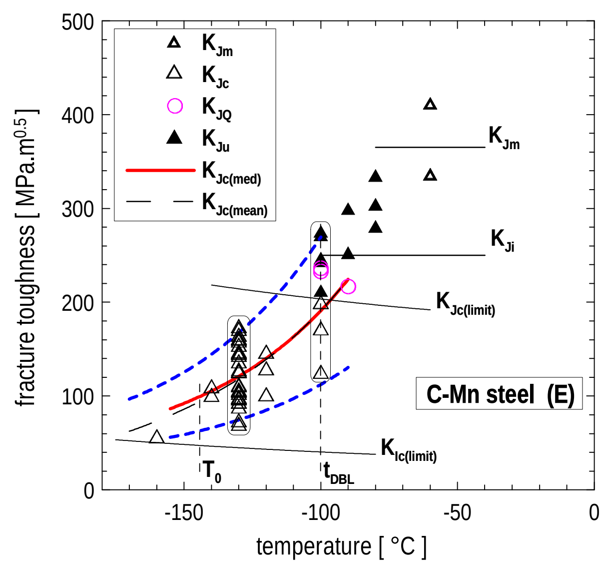

Fig. 2 Fracture toughness temperature diagram for surface part of the plate (location E)

Based on Figures 1 and 2 and other experimental results the fracture behaviour in transition region could characterised by the following way:

- The master curve methodology may be applied to predict the fracture toughness behaviour for the fracture toughness values being below T_0 + 46 °C, i.e. practically in the whole range of transition region of lower shelf.

*) The other approaches to reference temperature determination, namely the effect of number of specimens tested (up to 25) on the reference temperature is under study at this point [22, 25].

- The sharp transition of fracture toughness to much higher values of K_{Jc} occurs at the temperature T_0 + 26 °C. But it must be emphasised that for those specimens having these high values of K_{Jc}, fracture was initiated by cleavage thus indicating that the C-Mn cast steel has large intrinsic resistance to ductile tearing.
- Similar finding can be obtained when assessing the material causes of such large scatter of K_{Jc} values obtained at one test temperature (at –120 °C for location C and at –130 °C for location E). As it has been found by fractographic analysis [25] large amount of plastic deformation work at crack tip was needed before the unstable fracture initiation in order to get the crack tip radius nearly 50 μm for specimens in upper part of scatter. For specimen at lower part of scatter the same characteristic reaches the value of no more than 10 μm.
- When comparing the fracture behaviour of central part and surface location of thick walled plate it is seen that the differences are relatively small. Usually, nearly one half of fracture toughness values are observed in central parts of thick wall plate when compared to surface layers for forged materials of similar thickness [28]. Except for nearly comparable level of average fracture toughness values for both locations of cask segment this small difference is obvious from the shift of temperature t_{DBL} (the lowest value of brittle to ductile transition temperature displaying some amount of crack growth before the unstable fracture, see the Figures 1 and 2). The shift of reference temperature T_0 between both locations C and E is only slightly higher. This advantageous material fracture behaviour is partly result of optimal metallurgical technology but mainly the result of application of intercritical heat treatment developed for these particular applications.

Table 1 Reference temperatures obtained for both locations, different specimen configurations and loading rates

location	SENB – statically	PCVN - statically	SENB – dynamic. quasistatic method	SENB – dynamic. DKC method	PCVN - low blow quasistatic method
C	-126	-127	0	-14	9
E	-144	-144	-8	- 8	- 5

The Dynamic Fracture Toughness and The Effect of Loading Rate on Reference Temperature T_0

As generally known for dynamic tests the load - deflection traces are associated with oscillations that complicate the assessment procedures of fracture toughness determination. For purposes of this investigation two methods have been applied.

In case the fracture load can be read exactly from load deflection trace the quasistatic approach can be still applied. Except for standard 1T SENB specimens the PCVN specimens have been assessed by this method.

For evaluation tests at higher loading rates the dynamic key-curve method [27] can be applied supposing onset of unstable fracture is determined by some supported method. Magnetic emission method was used for these purposes. This approach was applied for specimens tested with drop weight tower [26]. The basis of the dynamic curve method is that the dynamic fracture toughness is the product of two parts, the quasi-static fracture toughness (K_I^{qs}) and the dynamic correction function (k^{dyn}):

$$K_{Id} = K_I^{qs} \,.\, k^{dyn} \tag{4}$$

In this equation the first part is derived analytically from a mass-spring model. The second part, the k^{dyn}, in other words the dynamic key-curve (DKC) function, is the measure of the dynamic effects. If the geometry of the test arrangement and the machine set-up are fixed, the K_{Id} can be expressed as a function of:

$$K_{Id} = \frac{Y \cdot E \cdot v_0}{\sqrt{W \cdot C_s^* \cdot \left(1 + C_m / C_s\right)}} \cdot t_f \cdot k^{dyn}(t = t_f) \tag{5}$$

where Y = Y (a/W) is the relationship for static K_I determination, E is the elastic modulus, v_0 is the impact velocity, W is the width of specimen, C_m is the machine compliance (1.22e-8 m/N), C_s is the specimen compliance, C_s^* is the dimensionless specimen compliance = f (a/W), t_f is the time-to-fracture and k^{dyn} is the dynamic key curve = f (t).

The machine compliance was calculated from a pre-test at low impact velocity with an unnotched specimen:

$$C_m = \frac{\frac{v_0}{dP} - C_{s,0}}{dt_{MLL}} \tag{6}$$

where v_0 is the impact velocity of the pre-test, dP/dt_{MLL} is the slope of the mean load line in the pre-test and $C_{S,0}=20.1/(E^*B)$ is the compliance of the unnotched specimen.

Although the dynamic effects were high enough to make the standard evaluation procedure impossible, it does not necessitate the correction of the dynamic key curve function. If the time to fracture falls into the range: $t_f \geq 9.2 * W/c_1$, the k^{dyn} part can be neglected. Here the c_1 is the longitudinal wave propagation speed in the given material calculated from:

$$c_1 = \sqrt{\frac{E}{\rho \cdot (1 - v^2)}} \qquad (7)$$

All of the time to fractures in these experiments fell into this time range, so $k^{dyn} = 1$ was used.

All the data obtained by both methods applied (quasistatic – QST and dynamic curve method – DKC) are summarised in Figures 3 and 4. Both data sets are plotted in these figures commonly with the results of reference temperature determination (see also Table 1) and master curves. In both cases the 90 % probability scatter band corresponds well to the given data (QST or DKC correspondingly). For central part of the plate (location C) substantial difference between both methods of K_{Jd} determination has been found. For surface location (E) quite different, i.e. more consistent results have been obtained. Although differences have been found between separate specimens assessed either by QST or by DKC method, the resulting properties of data set are practically the same. This can be seen on the same value of reference temperature and in the same localisation of master curve on temperature axis.

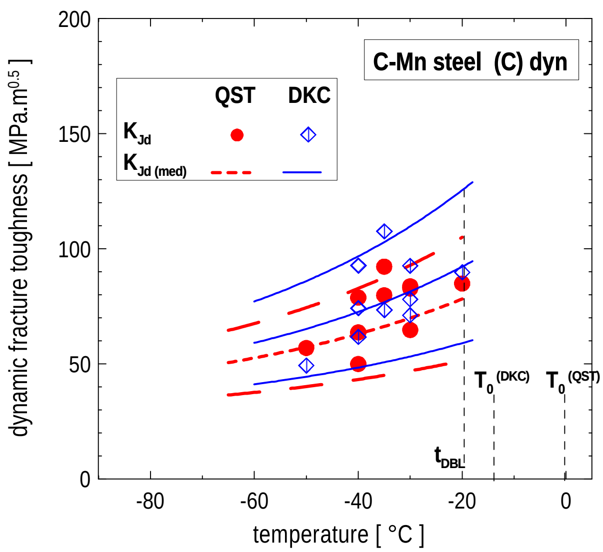

Fig. 3 Comparison of K_{Jd} and corresponding master curves in lower part of transition for loc. C

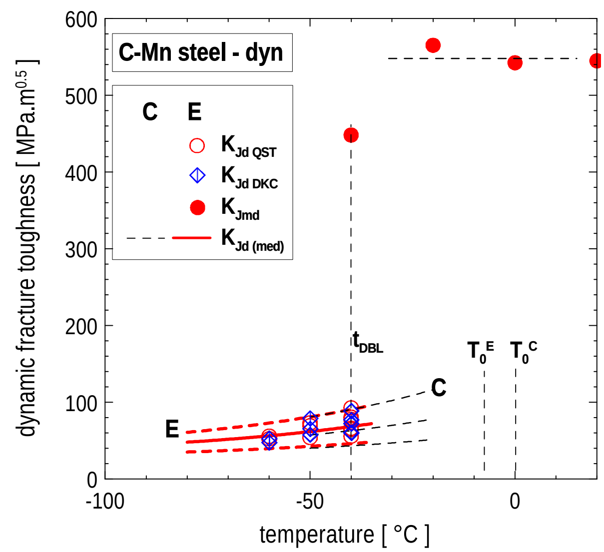

Fig. 4 K_{Jd} values and master curves in lower part of transition for loc. E and comparison to loc. C

When arising from the results obtained the following remarks have to be addressed:

- At dynamic loading the onset of unstable fracture is usually associated with adiabatic heating localised into plastic zone at crack tip. As the result of this specimen behaviour sharp, discontinuous, increase of fracture toughness values is usually observed instead of continuous curve. This is the typical material behaviour in transition region that specimen fails either completely in brittle manner or completely by ductile mechanism. Generation of data for purposes of master curve evaluation or similar purposes is thus very complicated.
- The highest temperatures that supplied valid experimental fracture toughness values and data for master curve determination are well below the reference temperature obtained. The difference is more than 20 °C for location C and more than 40 °C for location E. Although good correlation has been found as for mean values so for scatter characteristics, the highest temperature displaying the unstable fracture initiation limits also the validity of master curve.
- One of the main characteristics of material investigated is its strong susceptibility to loading rate. Remarkable shift of reference temperature and/or other transition temperatures is observed being on level of more than 120 °C for location C

and 130 °C for location E when comparing these temperatures with values obtained at static loading (dK/dt about 10^5 $MPam^{0.5}s^{-1}$ against 1 $MPam^{0.5}s^{-1}$).

- It has been proved experimentally that the effect of loading rate (dK/dt) on reference temperature (or shift of this temperature against the static loading) has more or less linear character (in co-ordinates with abscise in ln (dK/dt). In fig 7, the values obtained for cast ferritic steel are plotted (for both specimens locations) and compared to wrought CrMo steel [22]. Quite different behaviour of steel investigated could be assigned to two effects: (i) To the material susceptibility to loading rate and/or (ii) some uncertainty of reference temperature determination that is very highly above the highest test temperature displaying the unstable fracture.

Fracture Toughness Prediction by Using PCVN Specimen.

Pre-cracked Charpy type specimen (PCVN) is the most suitable geometry for the assessment of radiation and elevated temperature ageing of container cask steel as well as for analysis of strain rate effect. For PCVN specimens the similar data sets of fracture toughness as for standard specimens have been generated [25]. All the data from the PCVN specimens have been size corrected according to [9] by using the equation

$$K_{Jc(1T)} = 20 + (K_{Jc(10)} - 20)\left(\frac{B_{10}}{B_{1T}}\right)^{1/4} \tag{8}$$

From data meeting the validity limit Eq. (1) the reference temperature and master curves have been obtained. The reference temperatures are obvious from Table 1. For statically loaded PCVN specimens the reference temperature T_0 was estimated to be -127 °C, which is in good agreement with the value of T_0 = -126°C obtained by means of 1T specimens (for location C). The same temperature T_0 = -144°C was obtained for both specimen geometries for the location E; the master curve $K_{Jc(med)}$ and tolerance bounds for 5 and 95% fracture probability data obtained from the PCVN specimens are plotted in Fig. 5. All fracture toughness data of the 1T specimens (open triangles) fall inside the scatter band of PCVN specimen assessed by the above-mentioned procedure, thus verifying for the steel investigated the potential of utilising small pre-cracked specimens for the fracture toughness evaluation in the transition region.

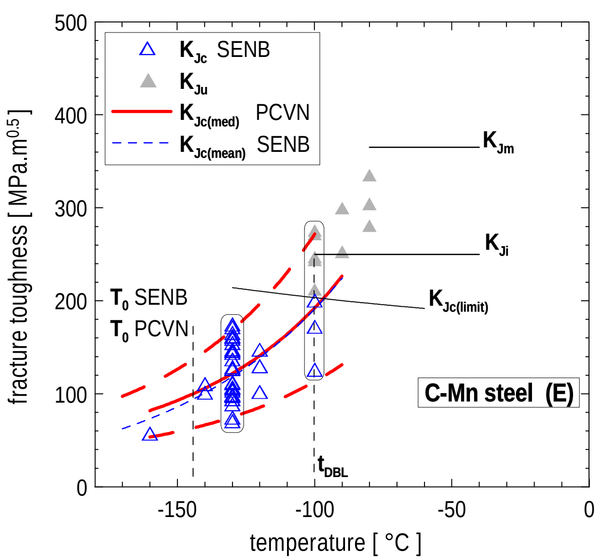

Fig. 5 Prediction of 1T specimen behaviour using the PCVN specimen for static loading (loc. E)

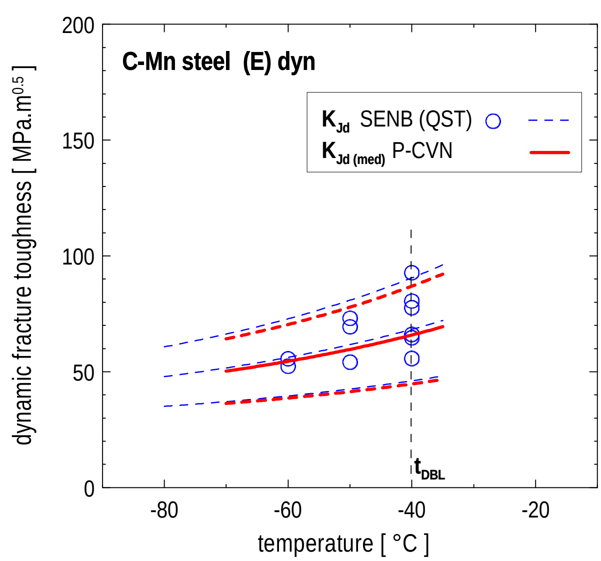

Fig. 6 Predictions of 1T specimen behaviour using the PCVN specimen for dynamic loading (E)

The above-mentioned approach is applicable in case there are enough number of valid K_{Jc} values available, i.e. fracture toughness values meeting the validity condition. The data from PCVN specimen not meeting the $K_{Jc(limit)}$ may be adjusted for constraint as it has been shown in [22] applying the toughness scaling model [19,20]. Thus by combining adjustment according to the toughness scaling model [19,20] and size correction the master curve methodology is possible to apply for prediction of 1T specimen behaviour using data obtained from the pre-cracked Charpy type specimens.

When studying the validity of approach for dynamic fracture toughness-temperature diagrams another possibility of the PCVN specimens use appears to be practicable. It follows from separate investigation [e.g. 29] and also our observation [22] that dependence of reference temperature on loading rate (reflected by dK_I/dt) has linear character in semi-logarithmic diagram. Very similar results have been obtained also for other low alloy steels and steel weldments [29]. It can be supposed that also for the cast steel investigated the linear dependence could be obtained. In Fig. 7, for our experimental values, this dependence is shown by full curve. Once this dependence is known it can be applied for prediction of 1T specimens transition behaviour from PCVN data tested dynamically. Such procedure could be reliable for application when small amount of material is available and static testing of small PCVN specimens is not providing valid K_{Jc} values. In this case the dynamic low blow test could provide the valid data for master curve determination and applying the shift of reference temperature (ΔT) prediction according to Fig. 7 the standard static fracture toughness transition could be predicted. Such procedure is under investigation now but some example is shown in Fig. 8. The separate empty triangles represent the experimental values from 1T specimens (the same as shown in Fig. 1) and curves represent the prediction obtained from PCVN specimen tested dynamically applying the shift of reference temperature read from the linear dependence of Fig. 7.

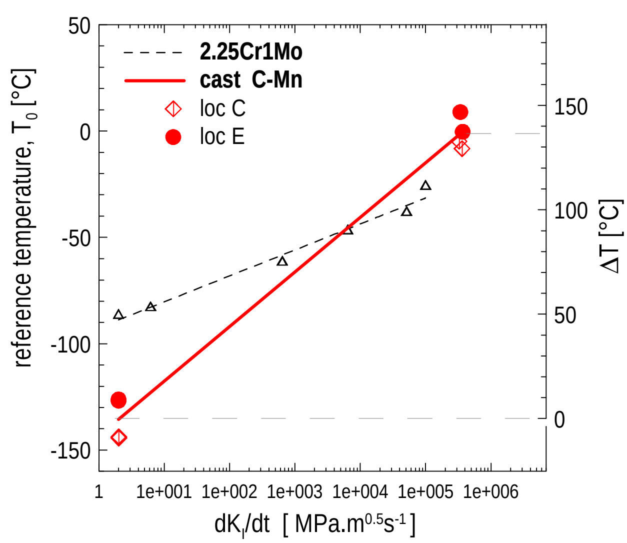

Fig. 7 Effect of loading rate on reference temperature

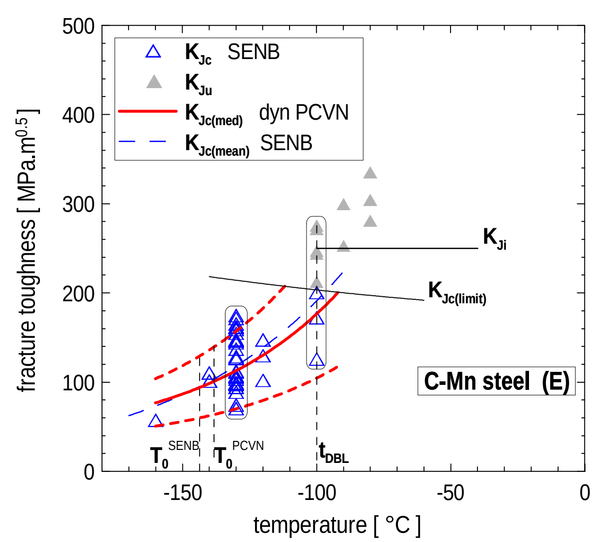

Fig. 8 Prediction of static fracture toughness from PCVN data obtained by low blow method

CONCLUDING REMARKS

In the investigation presented the fracture resistance of ferritic steel intended for casks of spent nuclear fuel has been analysed based on concepts of master curve applied.

Two procedures of dynamic fracture toughness determination have been applied. For surface location the same results (fracture toughness temperature diagram) has been obtained as for quasistatic so for dynamic key curve method.

The master curve concept has been shown to be valid in the lower part of transition range for C-Mn cast steel for both specimen locations investigated, i.e. for the central part and near surface layer of thick walled plate. Reference temperature T_0 determined using size corrected PCVN data obtained from static or dynamic testing was only slightly different from T_0 evaluated using 1T SENB specimens.

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