Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 86 (2014) 264 – 271
Procedia Engineering
www.elsevier.com/locate/procedia

1st International Conference on Structural Integrity, ICONS-2014

Study of Constraint Effect on Reference Temperature (T_0) of Reactor Pressure Vessel Material (20mnmoni55 Steel) in the Ductile to Brittle Transition Region

K. Bhattacharyya[a], S.K. Acharyya[a,*], J. Chattopadhyay[b] and S. Dhar[a]

[a]*Department of Mechanical Engineering, Jadavpur University, Kolkata-700032, India*
[b]*Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai-400085, India.*
[*]*E-mail ID: sanjib_acharyya@hotmail.com*

Abstract

The master curve methodology proposed by Kim Wallin (ASTM E1921-02) has been used to evaluate master curve and reference temperature (T_0) from TPB specimen for the material 20MnMoNi55 steel using single temperature and multi-temperature method. The effect of test temperature on reference temperature (T_0) has been studied for both TPB and CT specimens. A study is performed on the censor parameter M for both TPB and CT specimen and a correction value is suggested for TPB specimen for the material 20MnMoNi55 steel. To study the effect of constraint (a/w and thickness) on reference temperature (T_0), the value of (T_0) is calculated for different a/w ratio and thickness of TPB specimen. The results are compared with the results obtained from CT specimen for the same material to study the effect of geometry on reference temperature (T_0).

Peer-review under responsibility of the Indira Gandhi Centre for Atomic Research

Keywords: Master Curve, Reference temperature (T_o), TPB, Constraint

1. Introduction

Wallin [1] described the cleavage fracture toughness behaviour in the lower ductile -to-brittle transition (DBT) range of ferritic steels. The master curve together with an ASTM E1921 reference temperature (T_0) value defines the complete transition fracture toughness curve in a manner appropriate for use in both probabilistic and deterministic analysis. The master curve methodology [2] is based on a cleavage fracture model that assumes randomly distributed fracture initiators in a macroscopically homogeneous matrix. The transition curve definition for ferritic steels, as specified in ASTM E1921, was originally derived in 1991 from data measured on various quenched and tempered structural steels. After the statistical size correction of these data, which had been measured with different size specimens, the curve shape was determined from the maximum likelihood fit to the data and was

Peer-review under responsibility of the Indira Gandhi Centre for Atomic Research
doi:10.1016/j.proeng.2014.11.037

then proposed for a universal functional form of the temperature dependence of fracture toughness in the transition region and afterwards it was included in ASTM E1921. The master curve method allows the prediction of the fracture toughness curve in terms of the fracture toughness reference temperature (T_0), for any given fracture probability and any specimen thickness on the basis of small sized specimen testing. The master curve defines both the variation of the median value of fracture toughness with temperature and the scatter of fracture toughness about this median value. In the master curve method, a fracture toughness curve is described by a single parameter T_0 *(temperature* at which the median fracture toughness for one inch thick compact tension (1T–CT) fracture toughness specimen equals 100 MPa√m.) that establishes the position of the master curve on temperature scale.

The basis of the master curve approach is a three parameter Weibull model which the relationship between K_{JC} and the cumulative probability failure [Wallin, 2002, 2010]

$$P_f = 1 - \exp\left[-\left(\frac{K_{JC} - K_{\min}}{K_0 - K_{\min}}\right)^4\right] \tag{1}$$

where K_{JC} is the fracture toughness corresponding to P_f, K_0 is the fracture toughness corresponding to 63.2% cumulative probability and K_{min} is the lower bound fracture toughness. K_0 is a material property to be determined from experiment and K_{min} is taken to be 20 MPa√m.

Censoring is performed with respect to excessive ductile tearing prior to cleavage.

$$K_{JC(\text{limit})} \le \sqrt{\frac{b_0.\sigma_{ys}.E}{M.(1-\nu^2)}} \tag{2}$$

Here, σ_{ys} is the yield strength at test temperature, b_0 is the initial ligament size ,W is the width of the test specimen, a_0 is the initial crack length and M is the size criterion constant (according to ASTM E1921–02 standard M = 30). sx

The statistical weakest line theory is used to model the effect of specimen size on the probability of failure in the transition region. In the next step, the measured K_{JC} values are adjusted to a specimen size 1T (25.4 mm), using the following equation,

$$K_{JC} = K_{\min} + \left[K_{JC(X)} - K_{\min}\right]\left(\frac{B_0}{B_{1T}}\right)^{1/4} \tag{3}$$

2. Evaluation of T_0 from Experimental Results

The value of T_0 can be determined from experimental K_{JC} values either at a single test temperature or at multiple test temperatures,

2.1 Single Temperature Evaluation Method [3]

The Weibull scale parameter, K_0 (corresponding to 63.3% failure probability) is based on the randomly censored maximum likelihood expression can be calculated as follows for a group of six or more valid K_{JC} tests,

$$K_0 = \left[\sum_{i=1}^{N} \frac{\left(K_{JC(i)} - K_{\min}\right)^4}{N} \right]^{1/4} + K_{\min} \quad \text{MPa}\sqrt{\text{m}} \tag{4}$$

where $K_{JC(i)}$ is the individual $K_{JC(1T)}$ value and N is the number of K_{JC} values.

K_0 is related to the median fracture toughness as ,

$$K_{JC(med)} = K_{\min} + \left(K_0 - K_{\min}\right)\left(\ln 2\right)^{1/4} \ \text{MPa}\sqrt{\text{m}}. \tag{5}$$

The temperature dependence of the median fracture toughness of any ferritic steel is as,

$$K_{JC(med)} = 30 + 70\exp\left[0.019\left(T - T_0\right)\right] \ \text{MPa}\sqrt{\text{m}} \tag{6}$$

Here the reference temperature T_0 is the only material parameter. Thus, testing specimens at one single temperature, and estimating the median fracture toughness $K_{JC(med)}$ corresponding to the associated Weibull distribution, allows to estimate T_0 by

$$T_0 = T_{test} - \frac{1}{0.019}\ln\left[\frac{K_{JC(med)} - 30}{70}\right] \tag{7}$$

2.2. Multi-Temperature Evaluation Method

The multi-temperature option of ASTM E1921–02 represents a tool for the determination of T_0 with $K_{JC(med)}$ values distributed over a restricted temperature range, namely, T_0 = ±50°C. The value T_0 can be evaluated by an iterative solution of following equation. [4]

$$\sum_{i=1}^{N} \frac{\delta_i \exp\left[0.019\left(T_i - T_0\right)\right]}{11 + 77\exp\left[0.019\left(T_i - T_0\right)\right]} - \sum_{i=1}^{N} \frac{\left(K_{JC(i)} - K_{\min}\right)^4 \exp\left[0.019\left(T_i - T_0\right)\right]}{\left\{11 + 77\exp\left[0.019\left(T_i - T_0\right)\right]\right\}^5} = 0 \tag{8}$$

where , T_i is the test temperature corresponding to $K_{JC(i)}$,

δ_i is the censoring parameter: $\delta_i = 1$ if the $K_{JC(i)}$ datum is valid (equation 2)

$\delta_i = 0$ if the $K_{JC(i)}$ datum is not valid and censored.

Once T_0 is determined the master curve can be drawn (eq. 5) and the 5% and 95% tolerance bound curves are expressed using the following equations,

$$K_{JC5\%(1T)} = 24.5 + 37.8\exp\left(0.019\left[T - T_0\right]\right) \tag{9}$$

$$K_{JC95\%(1T)} = 34.6 + 102.2\exp\left(0.019\left[T - T_0\right]\right) \tag{10}$$

3. Material Details

The material used in the present study is 20MnMoNi55 steel which is a Reactor Pressure Vessel application steel. 20MnMoNi55 is basically a German designated material. A test block of this material is received from Bhaba Atomic Research Centre, India. The different chemical compositions of the material are given in Table 1.

Table1. Chemical Composition of 20MnMoNi55

Name of Element	C	Si	Mn	P	S	Al	Ni	Mo	Cr	Nb
Percentage Composition (in weight)	0.20	0.24	1.38	0.011	0.005	0.068	0.52	0.30	0.06	0.032

4. Experimental Details

Using INSTRON 8801 machine and liquid Nitrogen chamber the value of J_c are determined for CT [5] and TPB specimens for various samples of varying thickness, a/w ratio and temperatures following the methods as per ASTM E-1921. The Master curve along with the bounds and the values of T_0 have been determined for different samples as given in the test matrix. Results are presented in Table1.

5. Results and Discussion

CT Specimens

Dependence of T_0 on Test Temperature And Evaluation Method

From the results shown in table 2 and fig 2. and Fig 3 it is apparent that the variation in the value of T_0 is only 5^0 (4%). Table 2 and fig 1.,fig.2 and fig.3 show that the value of T_0 obtained from single temperature and multi temperature are also almost same for 1T CT, ½ CT and combined 1T CT, ½ CT. [6]

Dependence of T_0 on thickness and a/w ratio

From the results shown in table 2 and fig 1, fig 2., fig.3, fig.5 the values of T_0 is found to be independent of thickness if evaluated with thickness correction. The specimens having same a/w ratio or very small difference are taken together to compute T_0 and T_0 vs a/w ratio. From the results it is evident that the value of T_0 increases with a/w ratio.

Table 2: Test matrix for determination of T_0 and Master curve.

Sample no	Specimen	Thickness, mm	a/W ratio	Test Temp, (ºC)	T_0, (ºC)
1.	1T–CT	25	0.45–0.54	-110	–129
2.	1/2T–CT	12.5	0.45–0.54	-110	–126
3.	1T, 1/2T	25, 12.5	0.45–0.54	-80 to -140	–129
4.	1T–CT	25	0.45–0.55	-110	-130
5	½ T CT	12.5	0.45-0.55	-110	-130
7	½ T CT	12.5	0.45-0.55	-80	-127
8	1T -TPB	25	0.4-0.55	-110	-148
9	1T -TPB	25	0.4-0.55	-120	-156
10	TPB	25,12.5	0.4-0.55	-130	-150
11	1T -TPB	25	0.35	Multi-temp	-162
12	1T -TPB	25	0.4	Multi-temp	-145
13	1T -TPB	25	0.45	Multi-temp	-153
14	1T -TPB	25	0.5	Multi-temp	-157
15	1T -TPB	25	0.55	Multi-temp	-148
16	1T -TPB	25	0.6	Multi-temp	-155
17	1T -TPB	25	**0.4**	-110	-149
18	1T -TPB	25	0.45	-110	-145
19	1T -TPB	25	0.5	-110	-156
20	1T -TPB	25	0.55	-110	-153
21	1T -TPB	25	0.6	-110	-147
22	1T -TPB	25	0.65	-110	-159

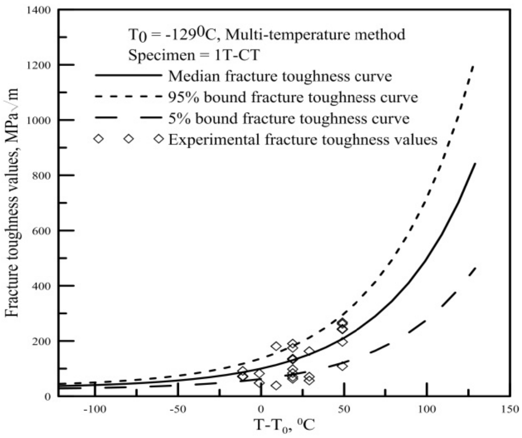

Fig 1. Master curve and T_0 of 1T CT specimens

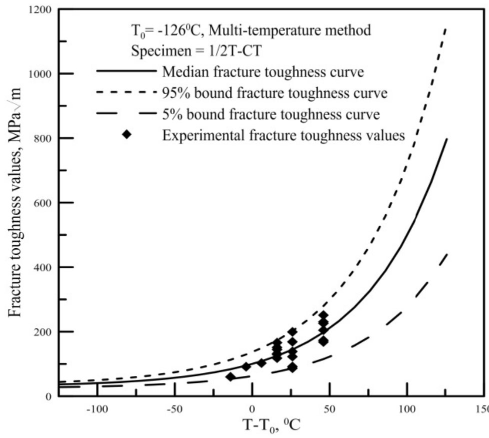

Fig 2. Master curve and T_0 of ½ T

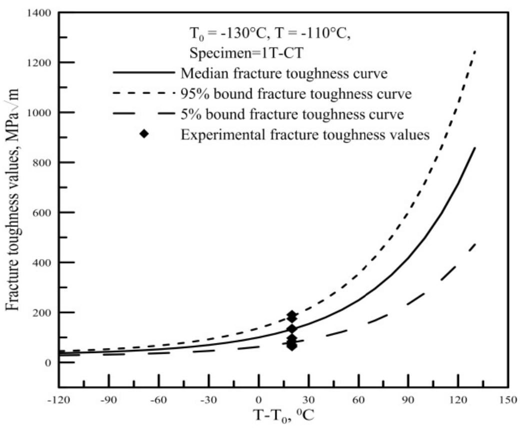

Fig 3. Master curve of 1T CT specimens

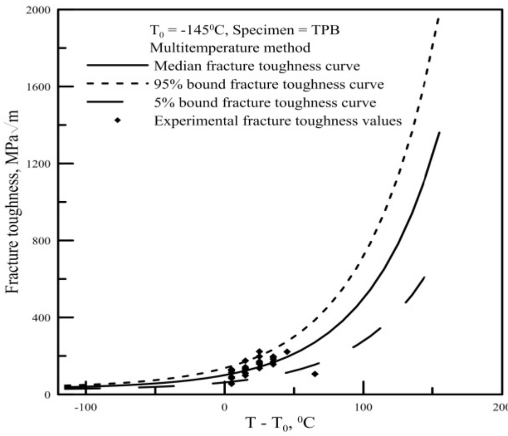

Fig 4. Master curve of TPB specimen

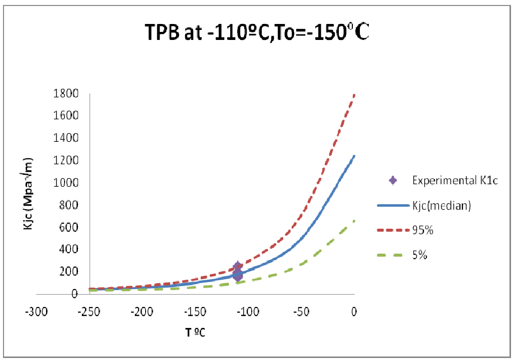

Fig 5. Master curve of 1T TPB specimens

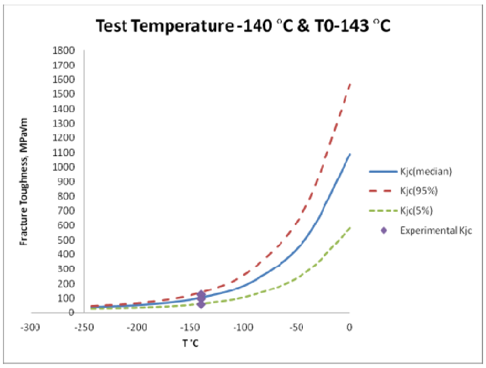

Fig 6. Master curve of TPB specimen

TPB Specimens

The value of T_0 for TPB specimens is evaluated at different test temperatures and also for multi temperature and the independence of T_0 on method (single temperature or multi temperature) and test temperature is observed for TPB specimens also as shown in table 2 and fig.4, fig.5 and fig6. But the value of T_0 is found to be lower than that of for CT specimens consistently in all cases. The loading type is different and constraint level is lower in case of TPB specimens compared to CT specimens and yields higher fracture toughness. This observation is in parity with results shown in CRP report[2]. The fracture toughness for TPB specimen of same geometry will be higher compared to CT specimen , Hence the limiting value of fracture toughness for TPB specimen should be computed with some higher value of M in eq.(2) to avoid specimen with excessive ductile stretch.

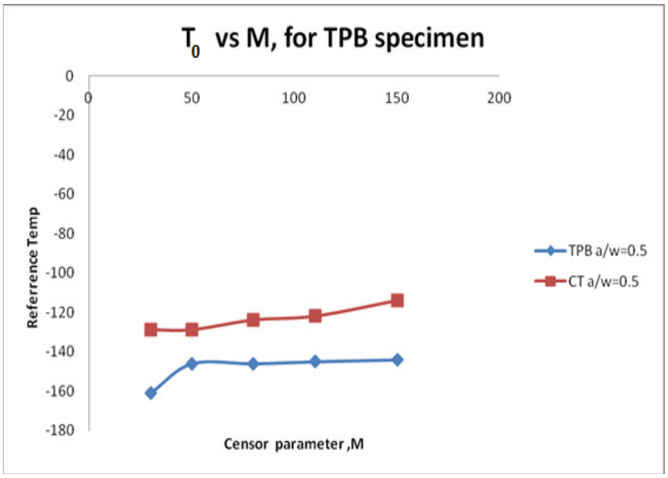

Fig 7.T_0 variation with M for TPB and CT specimens

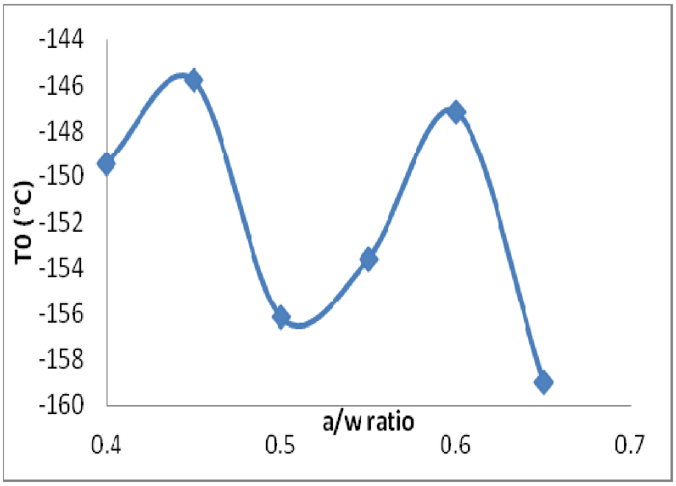

Fig 8. T_0 variation with a/W ratio of TPB

From the Fig 7, it is observed that the value of T_0 with increasing M for both TPB and CT specimen and saturates after M= 50 and M= 30 respectively. So the value of M can be taken as 50 for TPB specimen.

6. Conclusion

I. The master curve methodology for TPB specimen is well accepted for this particular RPV steel to characterize the fracture behavior in DBT region.
II. The value of T_0 obtained by Single Temperature at -110^{0}C matches with the multi temperature value. For the other Temperatures T_0 obtained by Single Temperature at -120^{0}C,-130^{0}C and -140^{0}C lies within a range of ±15^{0}C.
III. The reference temperature (T_0) depends on the geometry of the specimen
IV. From the experimental results it is observed that the value of M may be taken as 50 for TPB specimen instead of 30 as is taken for CT specimen

Acknowledgements

Authors acknowledge the support of Bhaba Atomic Research Centre, India for providing experimental infrastructure and material and technical support.

References

1. Wallin, K., 2002, Master curve analysis of the “Euro” fracture toughness dataset, Engineering Fracture Mechanics, 69, 451 – 481.
2. INTERNATIONAL ATOMIC ENERGY AGENCY, 2009b, Master Curve Approach to Monitor Fracture toughness of Reactor Pressure Vessels in Nuclear Power Plants, IAEA-TECDOC-1631, Vienna.
3. ASTM E1921-02. Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, http://www.astm.org/DATABASE.CART/HISTORICAL/E1921-02.htm.
4. Viehrig HW, Boehmert J, Dzugan J. Some issues by using the master curve concept. Nuclear Engineering and Design 2002; 212:115–24.
5. S.Bhowmik,A.Chattopadhyay’T.Bose,S.KAcharyya,P.Sahoo,J.Chattopadhay,S.Dhar.Estimation of fracture toughness of 20MnMoNi55 steel in the ductile to brittle transition region using master curve method.
6. Bhowmik, S. Sahoo, P. , Acharyya, S.K., Chattopadhyay, J., Dhar, S.' 2012, “Application and comparative study of the master curve methodology for fracture toughness characterization of 20MnMoNi55 steel” Material and Design, Vol-39. Pp-309-317.