APPLICATION OF MASTER CURVE METHODOLOGY IN THE DUCTILE TO BRITTLE TRANSITION REGION FOR THE MATERIAL 20MnMoNi55 STEEL

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ABSTRACT

Fracture toughness is an important material property to assess the critical load for structural integrity of reactor pressure vessel steel. In this paper, Master Curve method proposed by Kim Wallin is used to estimate the fracture toughness of 20MnMoNi55 steel in the ductile to brittle transition regime. Reference temperature (T_0) is evaluated using both single temperature and multi-temperature method for one inch thick compact tension (1T-CT) and 1/2-CT specimens. Reference temperature (T_0) is also determined from Charpy V-notch test data and compared. Effect of selection of temperature range and number of test temperatures on the value of T_0 is also studied. The correction proposed for thickness adjustment has been verified. It is observed that Charpy test results yield lower values of unirradiated T_0 compared to 1T-CT specimen tests. It is also observed that most of the fracture toughness values fall between 5% and 95% boundary of fracture toughness curves for all the evaluations.

INTRODUCTION

Both the scatter of fracture toughness in the transition zone and temperature dependence of fracture toughness is captured and expressed through Master curve method [3]. The master curve methodology is based on modelling cleavage fracture toughness at a fixed temperature in the transition with a 3-parameter Weibull distribution and the proposition that the shape of the fracture toughness vs. temperature curve is identical for all ferritic steels but having difference in absolute position in the temperature axis. The particular position of the curve for a particular steel is given in terms of the fracture toughness reference temperature (T_0) which is defined as the temperature at which the median fracture toughness for a 1T (one inch thick) compact tension (CT) specimen equals to 100 MPa√m [4]. Thus 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. The master curve together with a reference temperature (T_0) value define the complete transition fracture toughness curve in a manner appropriate for use in both probabilistic and deterministic analysis. The master curve method is also used to construct a bounding curve on the fracture toughness. Typically a bounding curve with a 95% degree of confidence is used as lower bound on the fracture toughness. In this paper Master Curve method proposed by Kim Wallin is used to estimate the fracture toughness of the 20MnMoNi55 material in the ductile to brittle transition regime. Transition zone for the material is identified by Charpy impact test results. Then tensile properties are measured at different temperatures in the transition zone. Fracture toughness of 1T-CT and 1/2-CT specimens of the 20MnMoNi55 material is measured at different temperatures covering upper shelf to transition. For Cleavage fracture in the transition zone Weibull Parameters (K_{min}, K_0) are estimated from fracture toughness results obtained from the experiments. Then both the single temperature and multi-temperature analysis are used to determine the reference temperature for master curve of the material. The correction proposed for thickness adjustment has been verified. All the propositions described in Master curve methodology are verified for this particular steel and found to be satisfactory. Proposition regarding K_{min} is validated. Single and multi-temperature reference temperature estimation algorithm yield equivalent estimates. It is found master curves obtained from single temperature analysis fall between 5% and 95% bound fracture toughness curves obtained from multi-temperature evaluation. The effects of specimen thickness, a/w, testing temperature range and no. f test temperatures used to compute T_0 on the value of T_0 are also studied.

MASTER CURVE ANALYSIS

Master Curve Analysis for Charpy Test Data

Wallin showed that the brittle fracture probability P_f for a given temperature in the transition region is described by a three parameter Weibull model in the following form

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

where K_{JC} value is converted value of J_C equal to critical K obtained from J_C in MPa√m, K_0 is a scale parameter dependent on the test temperature and specimen thickness, and K_{min} is the minimum possible fracture toughness. In this study, Barsom and Rolfe's [5] correlation has been used to estimate the fracture toughness transition curve based on experimental Charpy absorbed energy as given below.

$$\frac{K_{IC}^2}{E} = 2.2 \times 10^{-4} (CVN)^{3/2} \quad (2)$$

The fracture toughness values obtained from Eq. (2) have been normalized to those of the 1T size using the following equation.

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

where B_0 is thickness of the tested specimen (side grooves not considered) in mm, B_{1T} is the thickness of 1T-CT specimen [4, 6].

Master Curve Analysis for Fracture Test Data

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 steel. The temperature dependence of the median fracture toughness in the transition region can be estimated from [7],

$$K_{JC(median)} = 30 + 70 \exp\left[0.019\left(T - T_0\right)\right] \quad (4)$$

Once T_0 is known for a given material, the fracture toughness distribution can be obtained as a function of temperature through Eqs. (1) and (4). Now both upper and lower tolerance bounds can be calculated using following equation [8].

$$K_{JC(0_{.XX})} = 20 + \left[\ln\left(\frac{1}{1 - 0_{.XX}}\right)\right]^{\frac{1}{4}} \left\{11 + 77 \exp\left[0.019\left(T - T_0\right)\right]\right\} \quad (5)$$

where $0_{.XX}$ represents the cumulative probability level.
Finally T_0 is compared by rearranging Eq. (4). The K_{JC} limit is calculated according to the ASTM E1921 standard.

Evaluation of T_0 from Single Temperature Test Data

For single temperature evaluation, the estimation of the scale parameter K_0, is performed according to following equation [9, 10].

$$K_0 = \left[\sum_{i=1}^{N} \frac{\left(K_{JC(i)} - K_{min}\right)^4}{N}\right]^{\frac{1}{4}} + K_{min} \quad (6)$$

Here $K_{JC(i)}$ is the individual $K_{JC(1T)}$ value and N is the number of K_{JC} values. The fracture toughness for a median (50%) cumulative probability of fracture is determined using the following equation.

$$K_{JC(median)} = K_{min} + \left(K_0 - K_{min}\right)\left(\ln 2\right)^{\frac{1}{4}} \quad (7)$$

Now the $K_{JC(median)}$ value determined for the data set at test temperature is used to calculate T_0 at $K_{JC(median)}$ of 100 MPa√m by using the following equation.

$$T_0 = T - \left(\frac{1}{0.019}\right)\ln\left(\frac{K_{JC(median)} - 30}{70}\right) \tag{8}$$

Evaluation of T_0 from multi-temperature test data

For multi-temperature evaluation the determination of T_0 is performed with K_{JC} values distributed over a restricted temperature range, namely, $T_0 = \pm 50^0$C. The value of T_0 is evaluated by an iterative solution of the following equation [3].

$$\sum_{i=1}^{N} \frac{\delta_i \exp[0.019(T_i - T_0)]}{11 + 77\exp[0.019(T_i - T_0)]} - \sum_{i=1}^{N} \frac{(K_{JC(i)} - K_{min})^4 \exp[0.019(T_i - T_0)]}{\{11 + 77\exp[0.019(T_i - T_0)]\}^5} = 0 \tag{9}$$

Here T_i is the test temperature corresponding to $K_{JC(i)}$ and δ_i is the censoring parameter.
$\delta_i = 1$, if the $K_{JC(i)}$ datum is valid. and $\delta_i = 0$, if the $K_{JC(i)}$ datum is not valid and censored.

MATERIAL DETAILS

The material used in the present work is 20MnMoNi55 RPV applications steel. It is a German designated material received from Bhaba Atomic Research Centre, Mumbai. The different chemical compositions of the material are given in Table 1.

Table 1: Chemical composition of 20MnMoNi55 steel.

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

EXPERIMENTAL DETAILS

For determining master curve various experiments has been performed on the 20MnMoNi55 RPV steel. Tensile tests are performed on round bar specimen according to ASTM E8 standard at different temperatures in the range between 22^0C and -140^0C to evaluate the yield strength, ultimate strength and modulus of elasticity of the material at different temperatures. All the tensile tests are done in the cryo-chamber attached to a computer controlled Universal Testing Machine with 100 kN grip capacity. The required zero and sub-zero test temperature are attained by flowing liquid nitrogen from fully automated self pressurized Dewar flask of 120 L capacity. To determine Charpy absorbed energy of the material Charpy impact test has been done according to ASTM E23 method with eleven numbers of specimens at temperature 25^0C, 8^0C, -10^0C, -27^0C, -45^0C, -62^0C, -80^0C, -97^0C, -115^0C, -132^0C and -150^0C.

The fracture toughness tests in this investigation are performed on standard 1T-CT and 1/2-CT specimen. All the CT specimen are machined according to ASTM E399-90 standard and pre-crack is introduced at room temperature according to ASTM E647 standard in the range of a/W = 0.45 – 0.50. All the pre-cracking experiments are carried out on servo-hydraulic universal testing machine using commercial da/dN (Fatigue crack growth rate per cycle) software at stress ratio (R) of 0.02 using initial frequency of 10 Hz and with a constant ΔK (increment stress intensity factor) of 30 MPa√m and later on the frequency is increased to 15 Hz. Now to determine *J*-integral values, the pre-cracked specimens are tested at different temperature range between 22^0C and -140^0C. The J_C fracture toughness program is used for *J*-integral testing to obtain J–Δa data on universal testing machine according to ASTM E1820. The required zero and sub-zero test temperature are attained by flowing liquid nitrogen.

RESULTS AND DISCUSSION

Tensile Test Results

The relations between yield and ultimate strength with test temperature are derived using best fit curve and the equations are given below.

Yield strength, $\sigma_{ys} = 0.0112T^2 - 0.0431T + 494.01$ (10)

Ultimate strength, $\sigma_{us} = 0.0058T^2 - 0.6817T + 644.81$ (11)

Here T is in ^{0}C and strengths are in MPa.

Charpy Test Results and Master Curve from Charpy Test Data

From the test results, it is found that the Charpy absorbed energy values start decreasing with decrease in temperature at about 0^0C and the sharp slope continues up to -100^0C and then gets saturated on further decrease in temperature. The test results fit well with the tangent hyperbolic curve (Fig.1),

$$C_V = 142 + 134.5\left(\frac{T + 47.3}{43.3}\right) \tag{12}$$

where C_V stands for Charpy impact energy in Joule and T is the test temperature in ^{0}C. Initial estimation of master curve reference temperature ($T_0 = T_{41J} - 24^0$C) for 1T specimen is found to be -114^0C . From the Charpy transition curve of the material, the linear elastic fracture toughness is estimated and finally the 1T-CT equivalent elastic plastic fracture toughness transition curve of the material is obtained. The K_{JC} values at different temperature from Charpy impact test are listed in Table 2.

Table 2: Results of fracture toughness from Charpy impact test data

Temperature, ^{0}C	CVN (KJ)	K_{JC} from CVN MPa√m	Yield strength, MPa	Thickness, m	K_{JC}(1T), MPa√m
-45	149.14	283.09	518.63	0.7448	634.65
-50	133.62	260.70	524.17	0.6184	556.80
-55	118.33	237.99	530.26	0.5036	481.80
-60	103.64	215.47	536.91	0.4026	411.58
-65	90.00	193.65	544.13	0.3166	347.58
-70	77.31	172.94	551.91	0.2455	290.74
-75	66.05	153.68	560.24	0.1881	241.40
-80	56.16	136.08	569.14	0.1429	199.48
-85	47.62	120.24	578.59	0.1080	164.51
-90	40.36	106.21	588.61	0.0814	135.80
-95	34.26	93.92	599.19	0.0614	112.55
-100	29.18	83.29	610.32	0.0466	93.93
-105	25.00	74.17	622.02	0.0355	79.15
-110	21.58	66.42	634.27	0.0274	67.50
-115	18.80	59.89	647.09	0.0213	59.89
-120	16.55	54.42	660.46	0.0170	54.42
-125	14.73	49.88	674.40	0.0137	49.88

Six fracture toughness dataset have been taken from the Charpy impact test data. The dataset are selected in the range from 100 MPa√m to 300 MPa√m (Kim et al, 2002) and these data are used to determine the reference temperature T_0 to generate master curve. The reference temperature value $T_0 = -122^0$C and the fracture toughness curve are shown in Fig. 2.

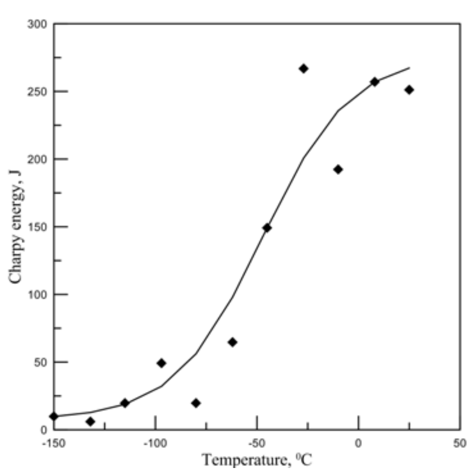

Fig. 1: Charpy energy vs. temperature.

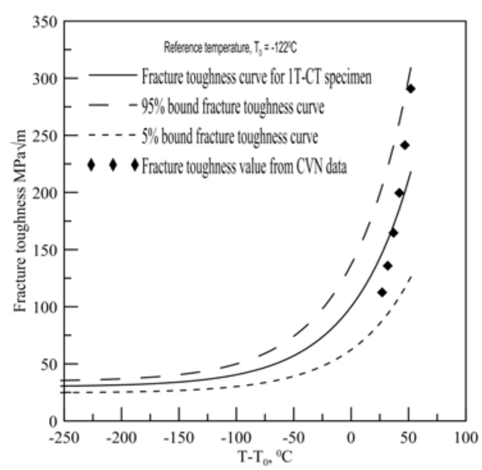

Fig. 2: Fracture toughness transition curve from CVN data

J-integral Test Results

J-integral test is performed according to ASTM E399-90 standard on 1T and 1/2-CT specimens at different temperatures in the range between 22^0C to -140^0C and a/W ratio. All the experimental result using 1T-CT and 1/2-CT specimen at different temperature and different crack length are shown in Fig. 3(a) and 3(b).

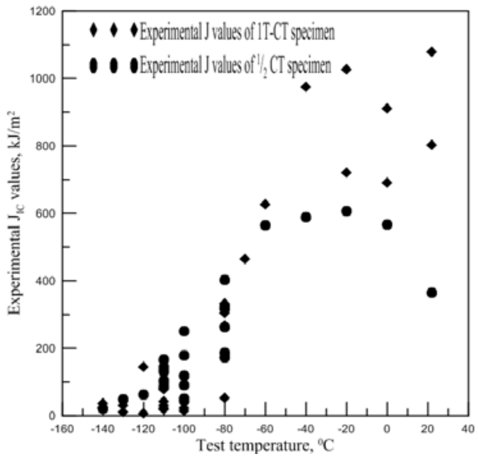

Fig. 3(a): Experimental fracture toughness values at different test temperatures.

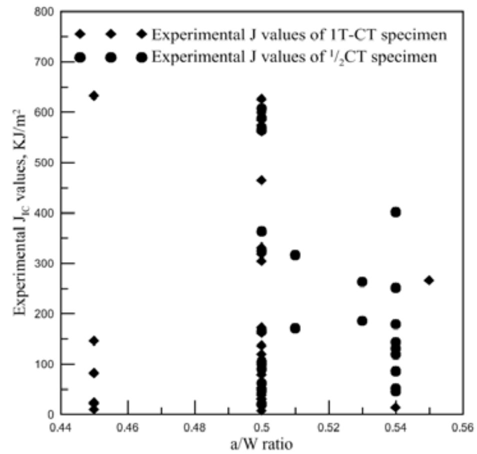

Fig. 3(b): Experimental fracture toughness values at different a/W ratios.

The fracture toughness values for only those specimens which have undergone brittle failure have been considered for master curve.

Table 3. Values of Reference temperature T_0 in ^{0}C

Specimen	Single temperature		Multi temperature
	-80 ^{0} C	-110 ^{0} C	
Full CT		-130	-129
Half CT	-126	-130	-126
Combined full and half CT	-130		

T_0 Estimation at Temperature -80^0C

The master curve combining both the specimens at -80^0C is shown in Fig. 4(a) and 4(b).

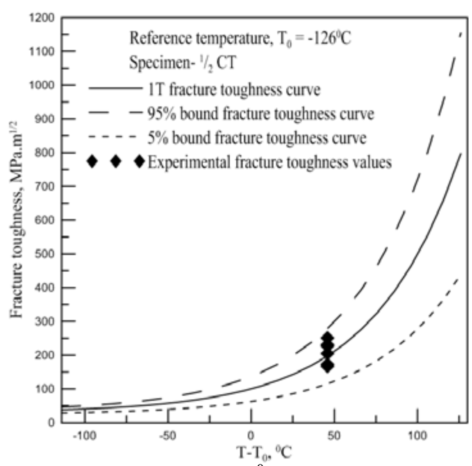

Fig. 4(a): Master curves at -80^0C test temperature for 1/2-CT specimen.

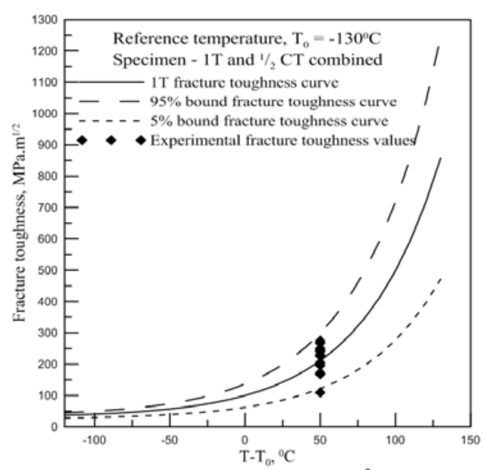

Fig. 4(b): Master curves at -80^0C test temperature for 1T and 1/2-CT combination.

T_0 Estimation at Temperature -110^0C

The master curve at test temperature -110^0C for 1/2-CT specimen is shown in Fig. 5(a) and 5(b).

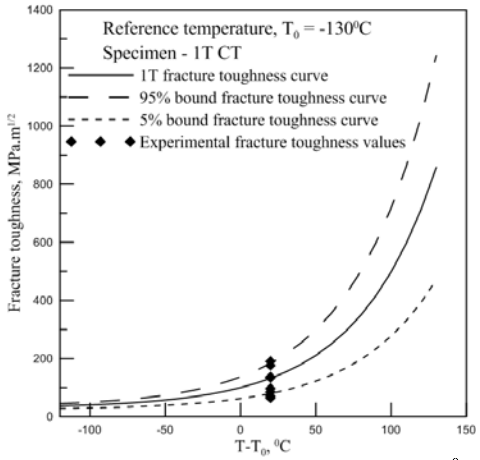

Fig. 5(a): Master curves at -110^0C
Test temperature using 1T-CT specimen

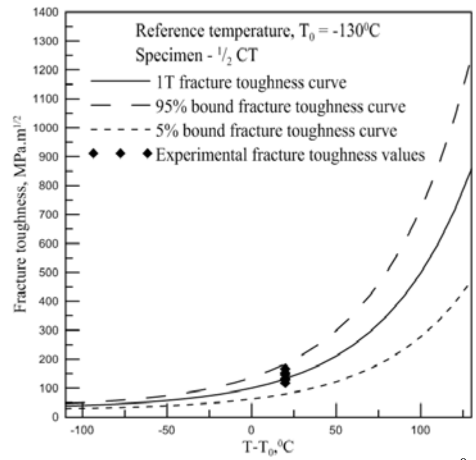

Fig. 5(b): Master curves at -110^0C
test temperature using 1/2-CT specimen.

T_0 Estimation using Multi-temperature Evaluation

In case of multi temperature evaluation different temperature sequences have been considered. The value of T_0 is -129^0C for 1T-CT specimen. The corresponding master curve is shown in Fig. 6(a). Similarly the value of T_0 using multi-temperature method is -126^0C for 1/2-CT specimen. The corresponding master curve is shown in Fig. 6(b). A number of master curves are obtained for the same material using different methods and specimens. All these curves are presented in the Fig. 6(e) for comparison with the master curve obtained using 1T and 1/2-CT specimens combined and using multi-temperature method.

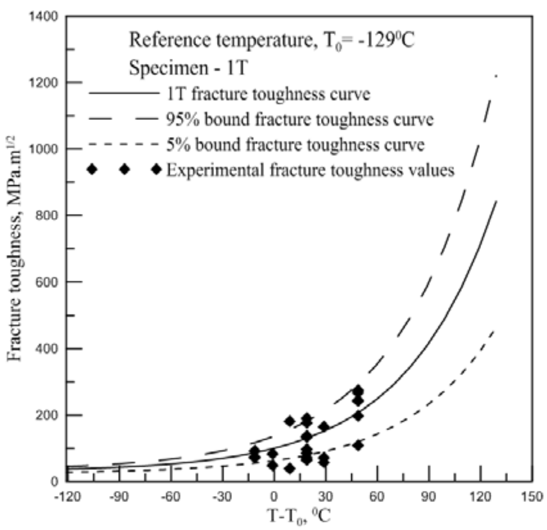

Fig. 6(a): Master curves from multi-temperature
evaluations using 1T-CT specimen

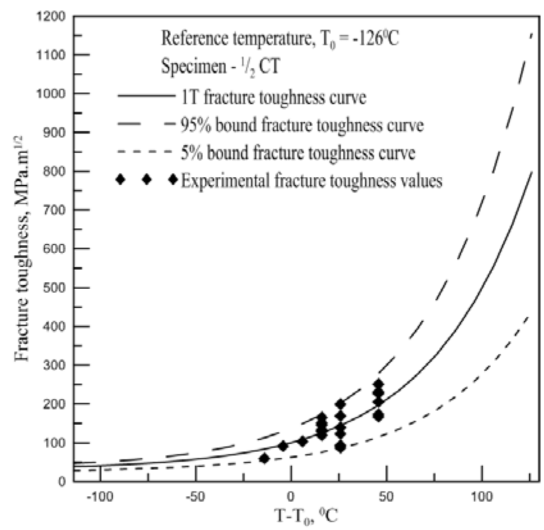

Fig. 6(b): Master curves from multi-temperature
evaluations using 1/2-CT specimen.

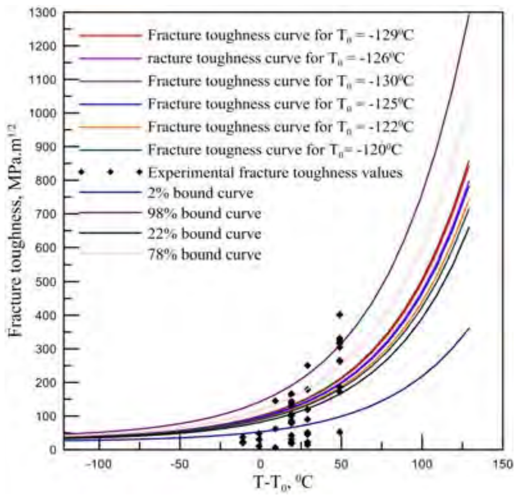

Fig. 6(e): Comparison in master curve for all the values.

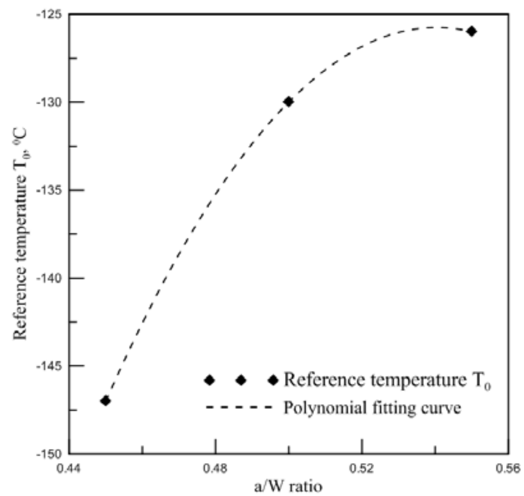

Fig. 6(f) T_0 vs. a/W ratio.

Effect of Test Temperature Combination and Temperature Range on Reference Temperature

The value of T_0 is estimated using 1T-CT and 1/2-CT specimen by multi-temperature evaluation for different combination of test temperature. When the data of two test temperature is used for evaluating T_0, the value of T_0 varies from -128^0C to -133^0C for 1T-CT specimen and from -124^0C to -129^0C for 1/2-CT specimen. When the data of three test temperatures are used the value of T_0 varies between -127^0C to -131^0C for 1T-CT specimen and -124^0C to -128^0C for 1/2-CT specimen. Also the range is -126^0C to -130^0C for 1T-CT and -123^0C to -126^0C for 1/2-CT when data of four test temperature is used. Pearson's product-moment correlation coefficient is used to measure the dependence of T_0 for both the cases of 1T-CT and 1/2-CT specimen with test temperature range. From the analysis it is has been found that as the temperature range increases the value of T_0 from consistent for both the specimen.

Effect of a/W for Fixed Thickness on Reference Temperature T_0

Specimens from both 1T-CT and 1/2-CT having same a/W ratio are taken together in a sample to evaluate T_0. K_{JC} values for 1/2-CT are adjusted with size correction. Thus values of T_0 are evaluated for a/W of 0.45, 0.50 and 0.55. From the result it is observed that as the value of a/W increases the value of T_0 also increases. Hence a dependence of T_0 on a/W ratio is found from the results.

K_{min} validation

The single temperature data is plotted into the probability diagram; it must be ordered by rank and designated rank probabilities. The three common estimates of the rank probability are

$P_{rank} = [(i-0.5)/n]$ 14(a) $P_{rank}=[i/(n+1)]$ 14(b) $P_{rank} = [(i-0.3)/(i+0.4)]$ 14(c)

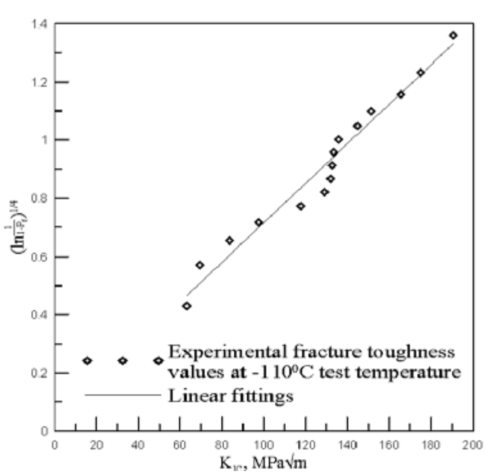

Fig. 7(a) Failure probability diagram from Eq. 14(a)

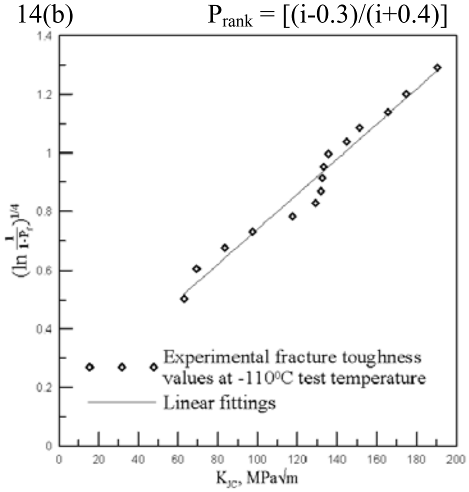

Fig. 7(b) Failure probability diagram from Eq. 14(b)

In Fig. 7(a) linear fitting is used to fit the experimental fracture toughness data to verify the K_{min} value using rank probability Eq.14(a). This fitting does not satisfy the K_{min} estimation, need more experimental value. In Fig. 7(b) linear fitting is used to fit the experimental fracture toughness data to verify the K_{min} value using rank probability Eq. 14(b). This fitting nearer to the K_{min} estimation, satisfy the experimental value. Similarly linear fitting is used to fit the experimental fracture toughness data to verify the K_{min} value using rank probability Eq. 14(c). This fitting does not satisfy the K_{min} estimation, need more experimental value.

CONCLUSION

Fracture toughness of 20MnMoNi55 steel is evaluated by Charpy impact test method and master curve method. Both the single temperature and multi-temperature analysis are used to determine the reference temperature for master curve of the material on CT specimen. From the present study, the following conclusions can be made:

i) Like other ferritic RPV steels, this material also shows the scatterness of the fracture toughness values in DBT region.
ii) Brittle fracture is observed at and below –80^{0}C.
iii) As expected, the reference temperature T_0 obtained from CT specimen fracture tests is less than the Charpy impact test data. The variation in T_0 between these two methods is ±5^{0}C.
iv) Although multi-temperature method is more effective way in estimating reference temperature, in the present study both single and multi-temperature estimation yield close result.
v) In case of multi-temperature evaluation T_0 is found to be more consistent when number and range of test temperatures increase.
vi) Considering fracture toughness curve derived from multi-temperature method as reference curve, it is found that most of the fracture toughness values fall within 95% and 5% bound confidence levels of the reference curve.
vii) For negligible variation in reference temperature derived from different methods and differently sized specimen one can derive the reference temperature by single temperature evaluation method and 1/2-CT specimens to reduce time, material utilization and cost also.

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