EVALUATION OF MASTER CURVE AND T_0 OF 20MNMONI55 STEEL FROM CT AND TPB SPECIMENS AND A COMPARATIVE STUDY

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ABSTRACT: Fracture toughness of ferritic steels in ductile to brittle transition temperature range is characterized by Master curve along with reference temperature T_0 as per guidelines prescribed in ASTM E-1921. The dependence of T_0 on specimen type, test temperature, method and specimen thickness have been studied for the material 20MnMoNi55 low carbon RPV steel. T_0 for CT and TPB specimens of different thickness, a/w ratio, test temperature have been found out using single temperature and multi temperature methods. The dependence of T_0 on test temperature and evaluation method is found to be insignificant for both CT and TPB specimens. The variation in T_0 for 1T and ½ T CT specimens (with thickness correction) is also found to be within 5%. The values of T_0 for TPB specimens are lower compared to CT specimens. The value of T_0 increases with a/w ratio for both CT and TPB specimens.

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 is based on a cleavage fracture model that assumes randomly distributed fracture initiators in a macroscopically homogeneous matrix. The generic form assumed for the fracture toughness versus temperature function makes the master curve model universal for practically all ferritic steels, provided the basic assumptions of the model are satisfied. 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. The determined good fit was 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. 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. In the master curve method, a fracture toughness curve is determined by a single parameter that establishes the position of the master curve on temperature scale. This parameter is termed as T_0 and is defined as the parameter at which the median fracture toughness for one inch thick compact tension (1T–CT) fracture toughness specimen equals 100 MPa√m.

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.

The single temperature data is presented in the original master curve failure probability diagram which produces a linear presentation of the master curve cumulative failure probability distribution by following equation,

$$\left\{ \ln \frac{1}{1 - P_f} \right\}^{1/4} = \frac{K_{JC} - K_{\min}}{K_0 - K_{\min}} \tag{2}$$

Compared to a normal Weibull probability diagram, the master curve failure probability diagram offers a better visualization of the data with respect to the master curve distribution. The master curve failure probability diagram should only be used in cases when the Weibull modulus is fixed as 4.

Two levels of censoring are applied in the standard master curve analysis. The fracture toughness data are classified as censored values when a test is stopped by unloading the specimen (δ_i = 0). Furthermore, all values of fracture toughness that are greater then the validity limit given by equation (2.10), as defined is ASTN E1921–02, are reduced to validity limit and treated as censored values. A similar censoring is performed with respect to excessive ductile tearing prior to cleavage.

$$K_{JC(\mathrm{limit})} \le \sqrt{\frac{b_0 . \sigma_{ys} . E}{M.\left(1 - \nu^2\right)}} \tag{3}$$

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

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,

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

where B_0 is the thickness of the tested specimen (side grooves are not considered), B_{1T} is the thickness B = 1T (25.4 mm), $K_{JC(1T)}$ is the fracture toughness of a specimen with a thickness of B = 1T, $K_{JC(X)}$ is the fracture toughness of the tested specimen, K_{min} is the lower bound fracture toughness fixed at 20 MPa√m in ASTM E1921–02. The lower validity criterion for the Weibull statistics, on which the master curve is based, is 50 MPa√m. The K_{JC} values below 50 MPa√m need not be size adjusted.

Single temperature evaluation method

Through the use of the Weibull statistics, it has been determined that ferritic steels within a specified yield strength range have a fracture toughness cumulative probability distribution of the same shape, independent of specimen shape and size. 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,

$$K_0 = \left[\sum_{i=1}^{N} \frac{\left(K_{JC(i)} - K_{\min}\right)^4}{N}\right]^{1/4} + K_{\min} \ \text{MPa}\sqrt{\text{m}} \tag{5}$$

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

The accuracy of the K_0 estimate will be a function of uncensored data $r = \sum_{i=1}^{N} \delta_i$. Then the term N is replaced by the number of valid K_{JC} values, r, if censored K_{JC} values are included in the calculation.

The reference fracture toughness K_0 is related to the median fracture toughness $K_{JC(med)}$ according to,

$$K_{JC(med)} = K_{\min} + \left(K_0 - K_{\min}\right)\left(\ln 2\right)^{1/4} \ \text{MPa}\sqrt{\text{m}} \tag{6}$$

For the median fracture toughness, a temperature distribution (master curve) according to

$$K_{JC(med)} = 30 + 70\exp\left[0.019\left(T - T_0\right)\right] \ \text{MPa}\sqrt{\text{m}} \tag{7}$$

Here the reference temperature T_0 is the only remaining 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

$$T_0 = T_{test} - \frac{1}{0.019}\ln\left[\frac{K_{JC(med)} - 30}{70}\right] \tag{8}$$

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, $T_0 = \pm 50$°C. The value T_0 can be evaluated by an iterative solution of following equation

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

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 9)

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

Once T_0 is determined, it is possible to estimate the whole transition region curve by means of the master curve and tolerance bound. The 5% tolerance bound curve is expressed using the following equation,

$$K_{JC5\%(1T)} = 24.5 + 37.8\exp(0.019[T - T_0]) \qquad (10)$$

The 95% tolerance bound curve is expressed using the following equation,

$$K_{JC95\%(1T)} = 34.6 + 102.2\exp(0.019[T - T_0]) \qquad (11)$$

In this work Master curve have been explored for the RPV material 20MnNiMo using CT and TPB specimens to study the effect of, test temperature, specimen thickness, a/w ratio on T_0 and Master curve in the transition range. Results from TPB specimens have been generated separately and compared with that of CT specimens. The constraint level and loading type is different in TPB specimens compared to CT specimens. Hence the effect of specimen type on T_0 is an important exploration in this work.

Experiments :

From Charpy test data it is revealed that transition temperature range for this material is around -100^0 C. Accordingly tensile tests at different low temperatures (20^0 C to -140^0 C) have been conducted to extract the temperature dependence of Yield strength, ultimate strength and modulus which are important input for fracture test in this temperature range. Then pre- cracking upto different a/w ratio and J-Integral test for CT and TPB specimens at different low temperatures have been performed to determine the K_{JC} values of the specimen.

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 sample as given in the test matrix.

Table 1: Test matrix for determination of T_0 and Master curve.

Sample no	Sample size(N)	Specimen	Thickness , mm	a/W ratio	Test Temp, (ºC)	T_0, (ºC)
1.	24	1T–CT	25	0.45–0.54	–80, –100, –110, –120, –130, & –140	–129
2.	21	1/2T–CT	12.5	0.45–0.54		–126
3.	45	1T & 1/2T–CT	25, 12.5	0.45–0.54		–129
4.	8	1T–CT	25	0.45–0.55	-110	-130
5	7	½ T CT	12.5	0.45-0.55	-110	-130
6		½ T CT	12.5	0.45-0.55	-100	-125
7		½ T CT	12.5	0.45-0.55	-80	-127
8	8	1T -TPB	25	0.4-0.55	-110	-148
9	7	1T -TPB	25	0.4-0.55	-120	-156
10	7	TPB	25,12.5	0.4-0.55	-130	-150
11	16	1T -TPB	25	0.4-0.6	Multi-temp	-145
12	12	1T -TPB	25	0.35-0.4	Multi-temp	-160
13	12	1T -TPB	25	0.4-0.45	Multi-temp	-153
				0.45-0.5	Multi-temp	-148
				0.5-0.55	Multi-temp	-145
				0.55-0.6	Multi-temp	-140

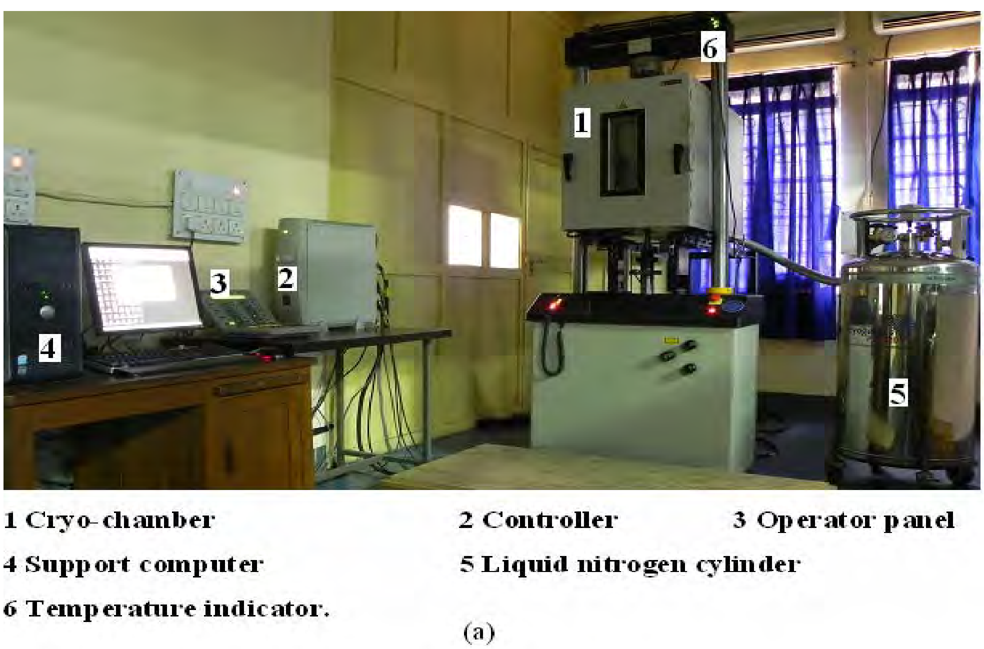


Figure 1. Photograph of 100 kN grip capacity Universal testing machine.

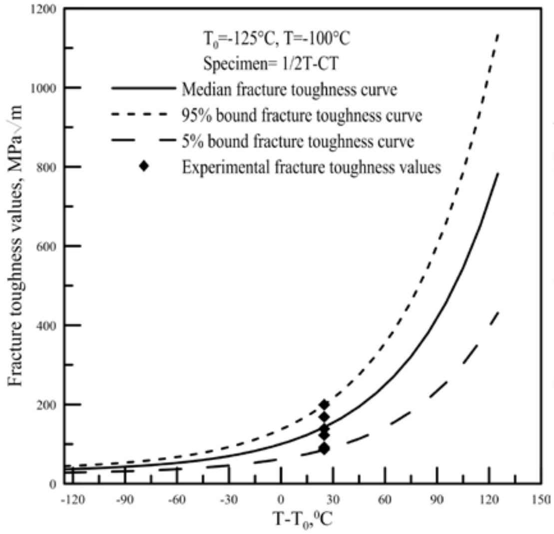
Results and discussion:

CT specimens :

a) Dependence of T_0 onTest temperature and evaluation method : The value of T_0 can be evaluated using ASTM E 1920 if the value of K_{JC} of at least six specimens are available either at a single test temperature or multiple test temperatures. If the values are at a single test temperature then T_0 is evaluated using single temperature method from eq. (8) and for multi temperature method eq. (9) is useful. The results of T_0 is evaluated at different single temperatures for 1T CT and ½ T CT specimens to explore the test temperature dependence of T_0. From the results shown in table 1 and fig 2. and Fig 3 it is apparent that the variation in the value of T_0 is only 5^0 (4%). Table 1 and fig 4 and fig.5 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.

b) **Dependence of T_0 on thickness :** Similarly the thickness dependence of T_0 is also attempted to study. The value of J_c can be determined experimentally for specimens of any thickness but the befor the evaluation of T_0 1T ((B= 25 mm)) equivalent K_{JC} is to be computed using thickness correction equation as given in eq. (4). It is proposed in Master Curve method (ASTM E 1920) that if thickness correction is done then the value of T_0 should be independent of specimen thickness. Here T_0 is evaluated using single temperature and multi temperature methods for 1T CT and ½ CT specimens separately and also for the sample taking together both 1T and ½ T CT specimens. For ½ T CT specimens thickness correction is done as specified in eq. (4). From the results shown in table 1 and fig 2, fig 3., fig.4, fig.5 the values of T_0 is found to be independent of thickness if evaluated with thickness correction.

c) **Dependence of T_0 on a/w ratio:** 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 is plotted in fig 11, From the results it is evident that the value of T_0 increases with a/w ratio. The trend of the T_0 vs a/w ratio curve appears to be similar for CT and TPB specimens both.



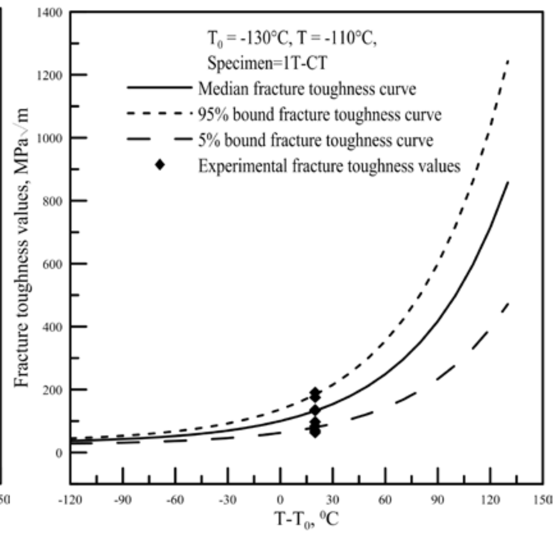
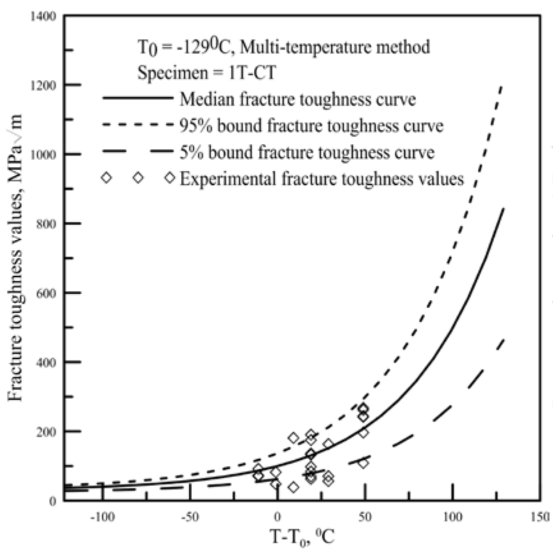


Fig 2. Master curve and T_0 of ½ T CT specimens (Single temperature)

Fig 3. Master curve and T_0 of 1T CT (Single temperature)



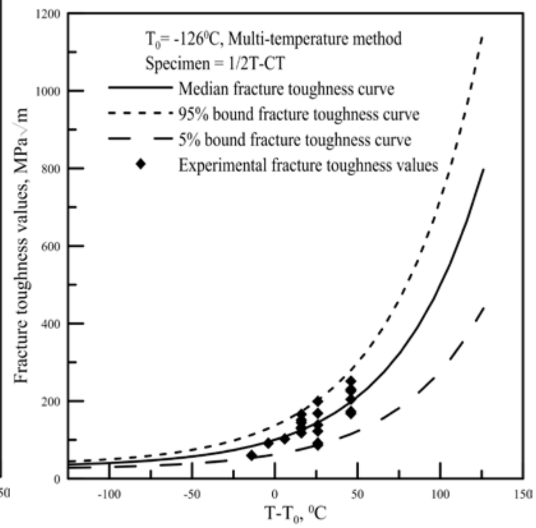


Fig 4. Master curve and T_0 of 1T CT specimens (multi-temperature)

Fig 5. Master curve and T_0 of ½ T CT (multi-temperature)

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 1 and fig.6, fig.7 and fig8. 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 higher in case of

TPB specimens compared to CT specimens. This observation is in parity with results shown in CRP report[2]. The T_0 vs a/w ratio for TPB specimens as shown in fig 11. shows the same trend like CT specimens [3].

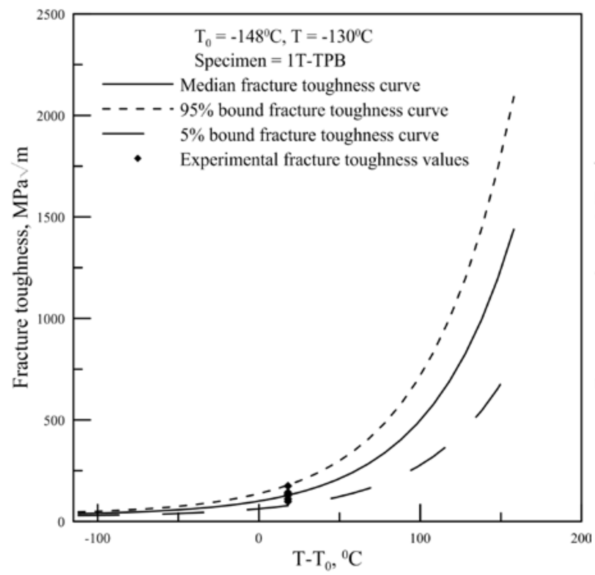


Fig 6. Master curve and T_0 (1T TPB) (Single temperature)

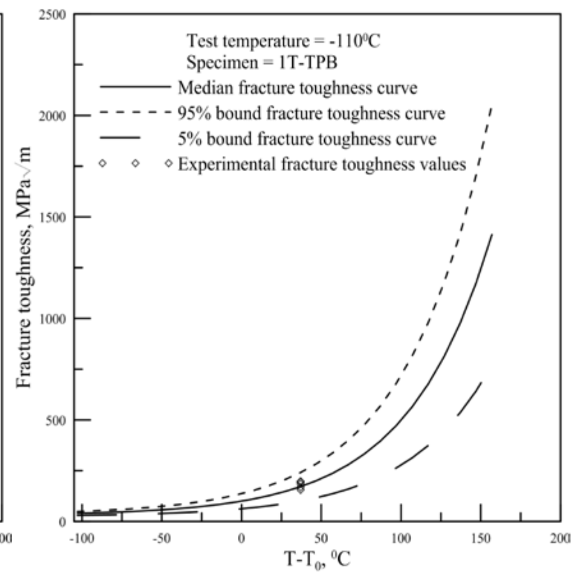


Fig 7. Master curve and T_0(-147^0C) 1T TPB (Single temperature)

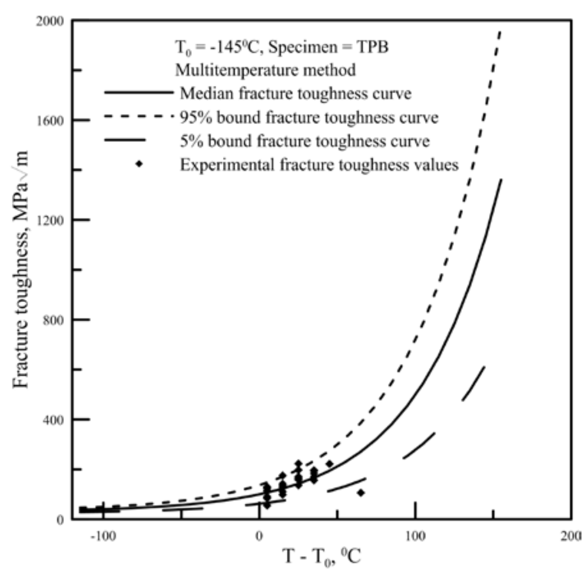


Fig 8. Master curve and T_0 (1T TPB) (Multiple temperature)

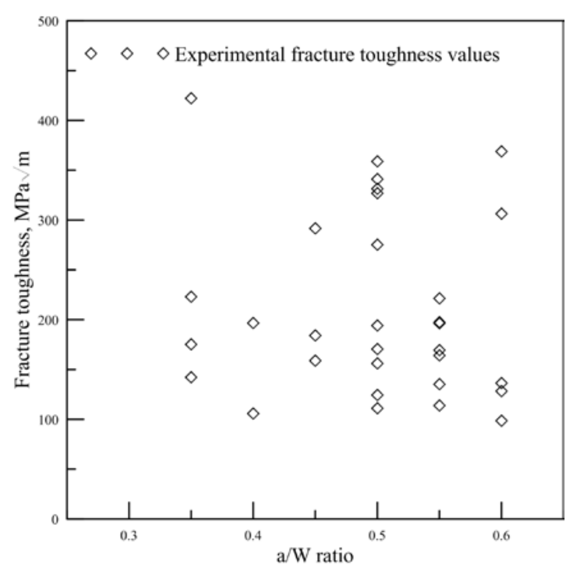


Fig.9. Exp. J_C values of 1T-TPB vs. a/w ratio

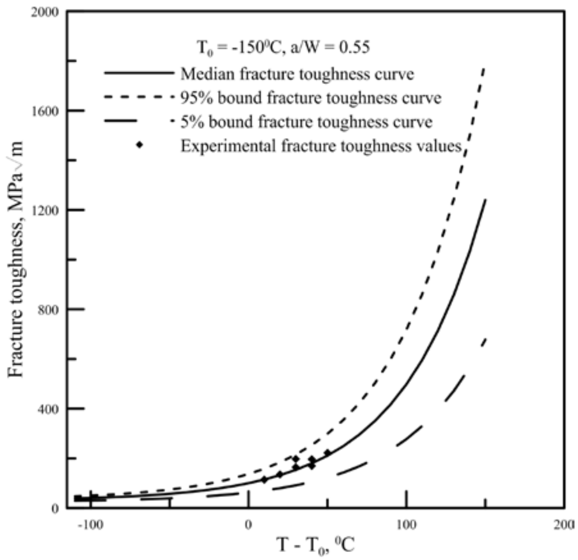


Fig.10. Master curve and T_0 (1T TPB)

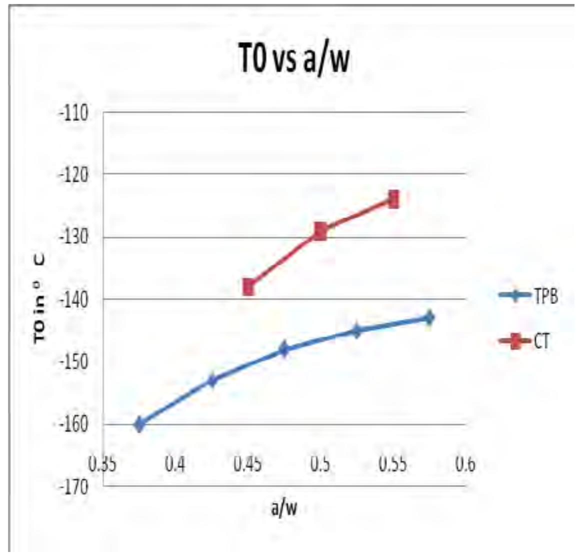


Fig.11. T_0 vs. a/w ratio (CT and TPB)

Conclusions

From the results it is observed that variation in T_0 evaluated using multi-temperature evaluation method for 1T–CT and 1/2T–CT specimens separately, is within ±3°C. Hence the correction suggested for thickness adjustment is found to be effective for this material. T_0 is almost independent of test temperature for both CT and TPB specimens. Single temperature and Multi-temperature methods are used to evaluate T_0 for 1T TPB specimens for different a/w ratios. The value of T_0 obtained for TPB specimens found to be lower than that of CT specimens due to variation in constraint level and matches with the CRP results. The variation of T_0 with a/w ratio shows similar trend in both CT and TPB specimens.

References:

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3. 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.