Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 14 (2019) 403–409

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity and Exhibition 2018

Master Curve of 20MnMoNi55 Steel From Miniature CT Specimens

Nevil Martin Jose[a]*, J.Chattopadhyay[a], P. V. Durgaprasad[a], N. Naveen Kumar[b]

[a]*Reactor Safety Division, BARC-Trombay, Mumbai 40008, India*
[b]*Materials Group, BARC-Trombay, Mumbai 400085, India*

Abstract

The steels used for manufacturing nuclear reactor pressure vessel are low alloy ferritic steels. There is a range of temperatures at which these steels exhibit transition from ductile to brittle fracture known as the ductile to brittle transition temperature (DBTT). In these range of temperatures, ferritic steels exhibit a scatter in the fracture toughness values having a characteristic statistical distribution which is unique to ferritic steels. The master curve methodology aims to capture this behaviour of ferritic steels through fracture mechanics principles. To obtain master curve, fracture experiments of standard specimens as per ASTM E-1921 must be carried out. Since reactor pressure vessel steels suffer loss in ductility due to irradiation embrittlement during its service life, master curve needs to be generated at periodic intervals using surveillance specimens. Use of standard sized fracture specimens as surveillance specimens are difficult as the space available in a nuclear reactor for keeping these specimens are limited. Also, the radiation dose associated with testing standard sized irradiated specimens can be dangerous for the personnel involved. Under these circumstances, it becomes necessary to carry out such tests using miniaturized specimens. In this work, we will obtain the fracture toughness master curve of 20MnMoNi55 steel (low alloy ferritic steel used for making nuclear reactor pressure vessels) from miniature CT specimens having a thickness of 4 mm.

Keywords: Master Curve; Reactor Pressure Vessel; Ductile to brittle transition temperature

Nomenclature	
a	Crack length of the fracture specimen
B	Thickness of CT specimen
b	Remaining ligament of CT specimen
E	Young's Modulus
K	Stress intensity factor
J	J-Integral
J_{el}	Elastic part of J-Integral
J_{pl}	Plastic part of J-Integral
N	Total no. of fracture tests
r	No. of valid tests
CT	Compact Tension Specimen (Fracture specimen)
P_L	Limit Load
σ_Y	Yield Stress

---

[*] Corresponding Author: Tel: 022-25596871

10.1016/j.prostr.2019.05.049

Email: nevil@barc.gov.in

1. Introduction

Master curve approach, is a fracture mechanics based approach used to obtain the fracture toughness of ferritic steels in the ductile to brittle transition temperature (DBTT) region. Master curve approach has been developed at VTT manufacturing technology by Kim Wallin et.al. (2001). Master curve is based on the property of ferritic steels that in the DBTT region, their fracture toughness follows a characteristic statistical distribution. In the master curve approach, fracture tests are conducted at a temperature range expected to be in the DBTT region. This expected test temperature may be obtained through Charpy impact tests, as explained in D. McCabe et.al. (2005). The fracture tests then conducted at this temperature, as described in ASTM E1921 gives the reference temperature T_0. The reference temperature T_0 can then be used for obtaining the fracture toughness curve named as the master curve, in the DBTT region.

Reactor pressure vessel (RPV), which are made of low alloy ferritic steels, needs to be ensured that under all operating conditions, is above the DBTT region. This ensures the structural integrity of the RPV by avoiding chances for brittle fracture. Irradiation of ferritic steels shifts the DBTT region to higher temperatures. So, the fracture toughness of RPV steels must be obtained at periodic intervals as the current DBTT region is dependent on the current irradiation level. This requires carrying out master curve experiments at periodic intervals.

Specimens known as surveillance specimens which are made of same material as RPV are put inside the RPV from the start so that the irradiation damage levels of the specimens are same as that of the RPV at any time. So, to obtain the DBTT region of RPV at any time, these specimens can be tested. However, to carryout tests as mentioned in the standards like ASTM E1921, the existing practise is to use specimens of relatively larger sizes. However, the space available inside RPV to keep surveillance specimens are limited. Also, irradiation doses associated with testing these specimens are more. If miniaturised specimens can be used for testing, these two problems can be reduced. In the literature, master curve generation from miniature specimens has been carried out by different researchers. For example, Masato Yamamato et.al. (2014) have carried out experiments to obtain master curve from miniature CT specimens. In this work, the applicability of using miniature CT specimens to determine the master curve of 20MnMoNi55 steel is investigated.

2. Experimental details

The material used for the present study is 20MnMoNi55 steel. This is a low alloy ferritic steel. Miniature CT specimens of dimensions shown in Fig. 1 has been used for the experiment. These specimens are similar to that had been used by Masato Yamamoto et.al. (2014).

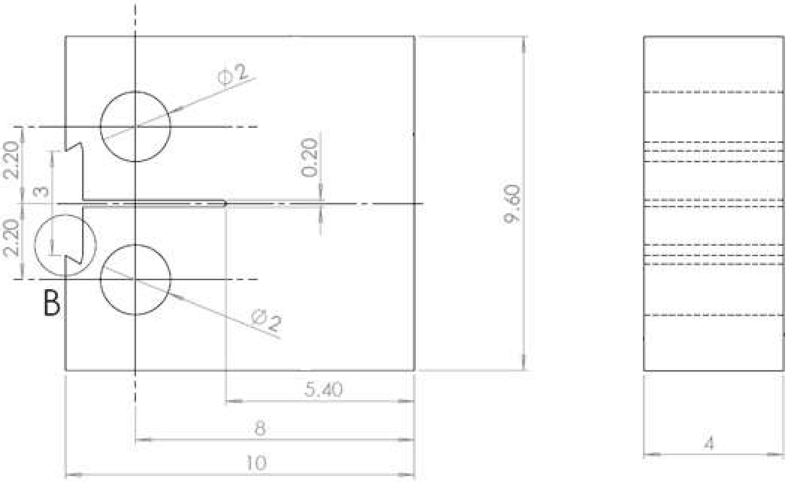

Fig. 1 Dimensions of MINI-CT specimen

The dimensions of the specimens are proportional as per ASTM E1921 standard. The experiments have been carried out on Dynamic Mechanical Analyser machine which can do both static loading and dynamic loading. Before carrying out the tests, the specimen surface was given a mirror finish by polishing using diamond paste having grit size 1µm. This is required to measure crack size during fatigue pre-cracking using optical methods. The experiment consisted of the steps explained below.

2.1 Fatigue precracking

The specimen was loaded using a pin and clevis arrangement shown in Fig. 2 (The pin and clevis were designed as per ASTM E1921. The clevis was made of heat treated 17-4PH stainless steel which has a high yield strength of 1379 MPa and a hardness of HRC 45. The pins were made of maraging steel).

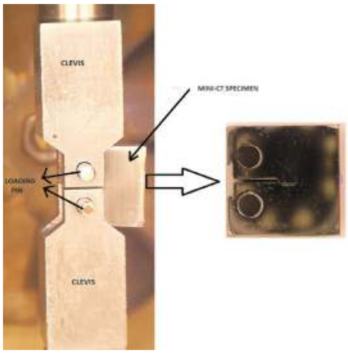

Fig. 2. The Pin and Clevis arrangement for specimen loading

The fatigue precracking was carried out using dynamic loading at 20Hz having a sinusoidal waveform. The maximum load during fatigue precracking (Pmax) was 30% of P_L of the specimen, calculated using the formula given in Eq.1 below. The equation was taken from literature by T. L Anderson (2011).

$$P_L = 1.072\eta B b \sigma_Y \tag{1}$$

where $\eta = \sqrt{\left(\frac{2a}{b}\right)^2 + \frac{4a}{b} + 2} - \left(\frac{2a}{b} + 1\right)$

The formula used is for plane stress case, since the specimen dimension was small. The min load was 0.1 times the maximum load. During fatigue pre-crack, the crack growth was monitored using a microscope having 20X magnification, which displayed images on a computer screen as shown in Fig. 3.

Fig. 3 Crack growth monitoring during fatigue precracking.

After the crack had grown to approximately 0.5 mm length, the fatigue precracking was carried out using a reduced load such that Pmax was equal to 25% of P_L. The fatigue precracking was continued till a/W ratio was approximately 0.5. After fatigue precracking has been completed, the crack lengths on both surface was measured using an optical microscope and average value of the crack lengths on both the surfaces was taken as the final fatigue pre-crack length. The final a/W ratios of the specimens tested are given in table 1, below.

Table. 1 Final a/W ratios of the MINI-CT specimens at the end of fatigue precracking

Specimen ID	*i* (specimen serial number)	a/W
MINI-CT-1	1	0.496
MINI-CT-2	2	0.471
MINI-CT-3	3	0.473
MINI-CT-4	4	0.447
MINI-CT-5	5	0.525
MINI-CT-6	6	0.497
MINI-CT-7	7	0.526

2.2 Fracture testing

The fracture testing was carried out at -100 degree Celsius. This temperature was selected for the test because this temperature was nearer to the T_0 temperature obtained for this material from standard specimens by D. McCabe et.al, 2005. The specimen is kept closed in the environmental chamber of the machine after holding it using the pin-clevis arrangement. The chamber is then cooled using liquid nitrogen. Once chamber temperature reached -100 °C, the chamber was kept at that temperature with the specimen inside for 1 hour. The specimen was then loaded in displacement control until fracture, with the temperature kept at -100° C. During the test, the load vs. load line displacement data of the specimen was recorded. A total of seven specimens were tested. All the tests were carried out at -100° C. Crack growth was not monitored during the fracture tests.

3. Results and discussions

3.1 Results

The load vs. load line displacement data obtained from experiments are used for calculating the reference temperature T_0. These experimental data are shown in Fig. 4.

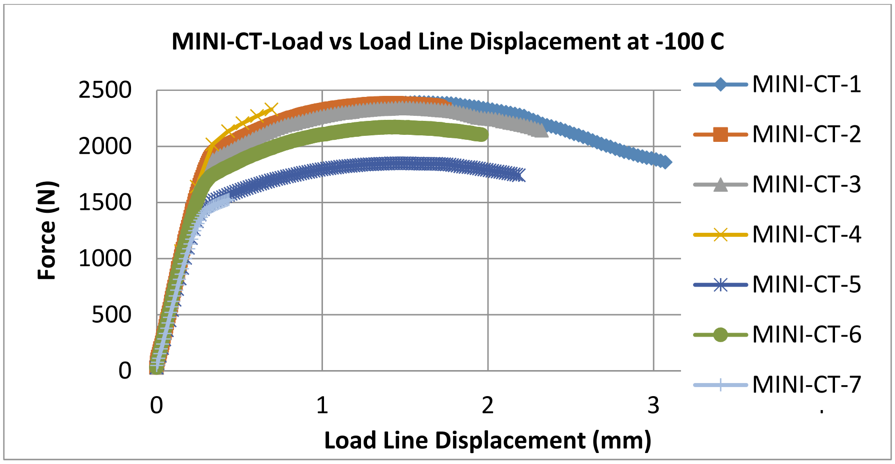

Fig.4 Experimental data – Load vs load line displacement data of fracture tests

The calculations are carried out as per the equations given in ASTM E1921 for single temperature tests. For calculations, the load vs load line displacement data up to maximum load point only is used. First, from the load vs load line displacement data, the applied J integral value is obtained by dividing the area under the data into elastic and plastic regions The elastic region gives J_{el} and the plastic region gives J_{pl}. The total applied J known as J_c is given by

$$J_c = J_{el} + J_{pl} \tag{2}$$

The J_c value obtained above is converted to K_{Jc} using the following equation

$$K_{JC} = \sqrt{J_C \frac{E}{1-\vartheta^2}} \tag{3}$$

The K_{Jc} value obtained above is then size adjusted for 1T CT specimens (specimens with B=25.4 mm i.e., 1 inch) using the following equation.

$$K_{JC(1T)} = 20 + \left[K_{JC(B\,miniCT)} - 20\right]\left(\frac{B_{miniCT}}{25.4}\right)^{1/4} \tag{4}$$

In the next step, the maximum allowable K_{JC} value for the given specimen is determined using Eq. 5. This value is then again size adjusted using Eq.4.

$$K_{JC(limit)} = \sqrt{\frac{Eb\sigma_{YS}}{30(1-\vartheta^2)}} \tag{5}$$

where σ_{YS} is yield stress of the material at fracture test temperature, equal to 610 MPa for 20MnMoNi55 steel. This data was taken from the work of S. Bhowmik et.al. (2011).

If the K_{JC} value obtained for a given specimen from experiment is more than its $K_{JC(limit)}$ value for that specimen, then for further calculations, the specimen's K_{JC} value is replaced by $K_{JC(limit)}$ value. All the values are obtained in MPa-m$^{1/2}$ in this work. The scale parameter K_o is then calculated using Eq.6

$$K_o = \left[\sum_i^N \frac{\left(K_{JC(i)}-20\right)^4}{r}\right]^{1/4} + 20,\ \text{MPa-m}^{1/2} \tag{6}$$

The $K_{JC(median)}$ value at the test temperature is then obtained by Eq.7

$$K_{JC(median)} = 20 + (K_0 - 20)[\ln(2)]^{1/4} \tag{7}$$

The reference temperature T_0 is then determined using Eq. 8

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

Once T_o is obtained, the median fracture toughness master curve for the material valid for the temperature range T_0 -50 to T_0 + 50, for 1T specimens is given by Eq. 9

$$K_{JC(median)} = 30 + 70exp[0.019(T - T_0)] \tag{9}$$

The upper and lower tolerance bounds of the master curve can be obtained using the following equation, Eq. 10.

$$K_{JC(0.xx)} = 20 + \left[ln\left(\frac{1}{1-0.xx}\right)\right]^{1/4}[11 + 77exp(0.019[T - T_0])] \tag{10}$$

where 0.xx represents the required cumulative probability level of failure.

The results obtained by carrying out the above-mentioned calculations are as given in Table. 2

Table 2. K_{JC} values obtained after calculations

i	$K_{JC(i)}$ (MPa-m$^{1/2}$)	$K_{JC(limit)}$ (MPa-m$^{1/2}$)
1	190.98	91.67
2	188.27	93.76
3	179.88	93.61
4	84.29	95.67
5	171.17	89.68
6	174.25	91.54
7	67.36	89.09

From the table, it is seen that only two specimens have their K_{JC} values less than their $K_{JC(limit)}$ values. So, the no. of valid tests, *r*, is only two. Other data needs to be censored with $K_{JC(limit)}$ values. (However, ASTM E1921 specifies that minimum six valid tests are required). The fracture toughness master curve obtained from this data set is given in Fig. 5. The reference temperature T_0 obtained from this data set is -109^{0}C. The value of T_0 obtained from D. McCabe et. al (2005) and S. Bhowmik et.al, (2011) for standard specimens are 120 ^{0}C and 129 ^{0}C, respectively

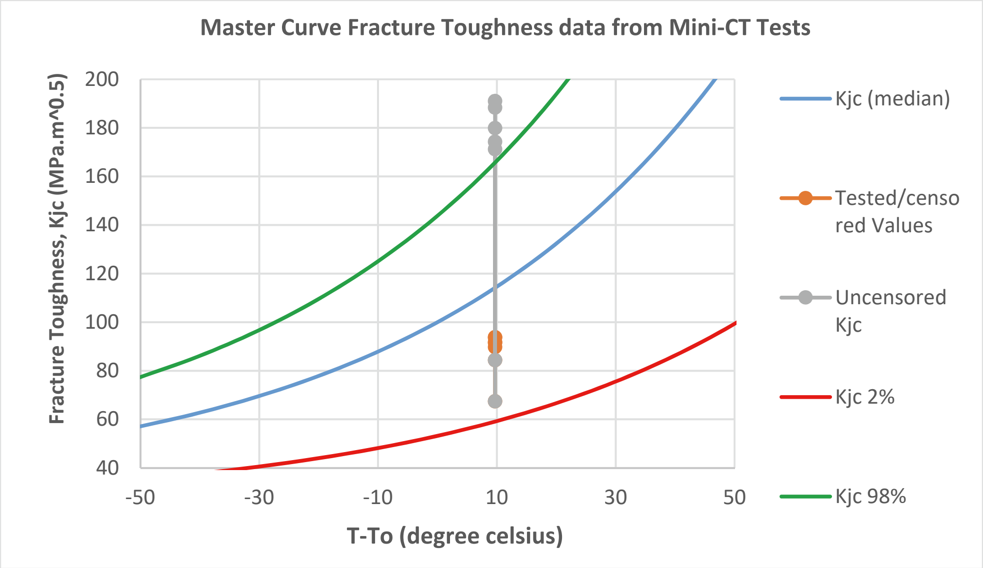

Fig. 5. Master curve obtained from the experimental data of this work for different cumulative probabilities of failure viz., 2%, 98% and 50%-median

3.2 Fractography

The fracture surface of MINI-CT-5 was examined using scanning electron microscopy. The fracture surface consisted of three regions viz., 1) Fatigue crack growth region, 2) A very small region showing ductile crack growth evidenced by void formation and second phase particles and 3) The large brittle fracture region showing river patterns of trans granular cleavage. These are shown in the images below

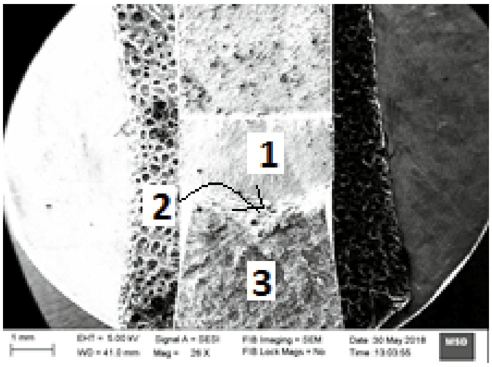

Fig. 6. Fracture surface of MINI-CT-5 showing three regions

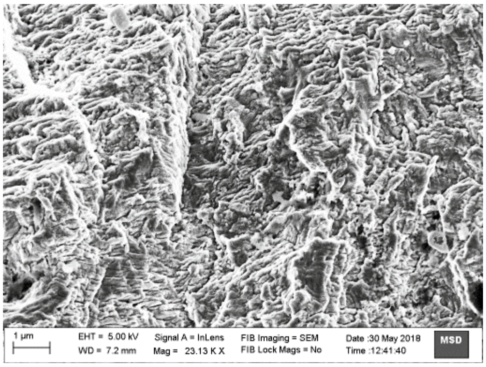

Fig. 7. Enlarged view of region 1 in Fig.5; shows striations due to fatigue crack growth

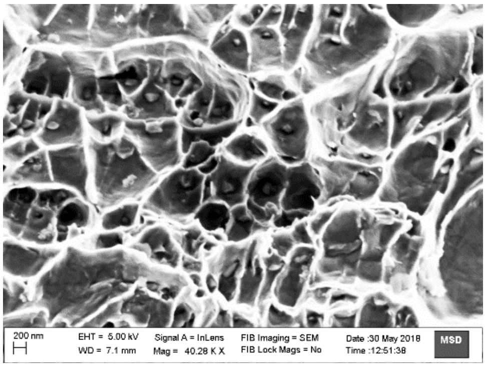

Fig. 8. Enlarged view of region 2, showing voids and second phase particles inside them. This region shows ductile crack growth.

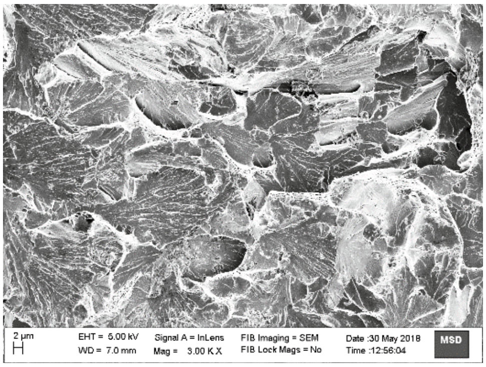

Fig. 9 Enlarged view of region 3, showing trans-granular cleavage – brittle fracture

4. Conclusions

1. The no. of valid tests obtained with miniature specimens are less when compared with similar tests (obtained from D. McCabe et. al (2005) and S. Bhowmik et.al (2011)) conducted on standard specimens.
2. The value of T_0 obtained from miniature specimens in this experiment is comparable to the values seen in literature, even though the no.of valid tests are less.
3. The fracture surface of the material shows that even in specimens which violated $K_{JC(limit)}$ criteria, the failure mechanism is by trans-granular cleavage type brittle fracture.

References

American Society for Testing and Materials. *E1921-97 standard test method for determining of reference temperature, T0, for ferritic steels in the transition range*. Annual Book of ASTM Standards 1999;03.01:1060–76

D. McCabe, J. Merkle, and K. Wallin, Eds., 2005. *An Introduction to the Development and Use of the Master Curve Method*, MNL52-EB, ASTM International, West Conshohocken, PA, 2005, https://doi.org/10.1520/MNL52-EB

Kim Wallin, Tapio Planman, Matti Valo, Rauno Rintamaa., 2001. *Applicability of miniature size bend specimens to determine the master curve reference temperature T_0*; Engineering Fracture Mechanics-Volume 68, Issue 11, July 2001, Pages 1265-1296

Masato Yamamoto, Kunio Onizawa, Kentaro Yoshimoto, Takuya Ogawa, Yasuhiro Mabuchi, Matti Valo, Marlies Lambrecht, Hans-Werner Viehrig, Naoki Miura, Naoki Soneda., 2014. *International Round Robin Test on Master Curve Reference Temperature Evaluation Utilizing Miniature C(T) Specimen*; Published Online: Aug 2014, Paper ID: STP157620140020

S. Bhowmik, A. Chattopadhyay, T. Bose, S.K. Acharyya, P. Sahoo, J. Chattopadhyay, S. Dhar., 2011. *Estimation of fracture toughness of 20MnMoNi55 steel in the ductile to brittle transition region using master curve method*; Nuclear Engineering and Design 241 (2011) 2831– 2838

T. L Anderson., 2011. *Fracture Mechanics: Fundamentals and applications;* Third edition, 2011, CRC Press.