DYNAMIC MASTER CURVE and DUCTILE-BRITTLE TRANSITION TEMPERATURE OF 9Cr-1Mo STEEL

A.MOITRA[1], P.R.SREENIVASAN[1], S.L.MANNAN[1] and V.SINGH[2]

[1]Materials Development Group. Indira Gandhi Centre for Atomic Research,Tamilnadu 603 102, India.
[2]Department of Metallurgical Engineering, Banaras Hindu University, Varanasi, India

ABSTRACT

The DBTT of 9Cr-1Mo steel has been characterised by reference temperature (T_0) based Master Curve (MC) approach. The MC was developed at the dynamic loading conditions (stress intensity factor change rate $\sim 10^6$ MPa√m/s at a loading rate of 5.12 m/s) using pre-cracked Charpy specimens (PCVN) following ASTM E 1921 guidelines. To minimise the inertial oscillations effect on load determination, the initial T_0 was determined by tests conducted at a hammer velocity of ~1.12 m/s; this was further converted to T_0 at 5.12 m/s applying an test velocity dependent shift to T_0. Thus, the T_0 for 9Cr-1Mo steel at dynamic condition was determined to be –52 ^{O}C. Using a modified Schindler procedure to evaluate K_{Jd} from instrumented Charpy V-notch tests, T_0 was also estimated for the 9Cr-1Mo steel and the result shows close agreement with the T_0 evaluated from the pre-cracked Charpy tests. ASME K_{IR}-curve approach proves to be too conservative compared to the real trend of the fracture toughness with temperature.

1. INTRODUCTION

Irradiation induced shift in ductile-brittle transition temperature (DBTT) of 9Cr-1Mo steel is a matter of concern in its application as a wrapper materials in fast reactors [1,2]. Thus it is essential to characterise the DBTT of the unirradiated material on the basis of dynamic fracture toughness variation in transition regime.

In describing the DBTT, the RT_{NDT} based K_{IR} curve [3,4] approach, being used since 1972, is purely empirical and based on the data obtained from reactor pressure vessel steels only. However, it is now well understood that the size, shape and distribution of the carbides ahead of the crack tip leads to scatter in fracture toughness. A description of brittle fracture mechanism through 'weakest link' theory [5] and subsequent modeling of scatter using a three parameter Weibull distribution recently has led to the development of Master Curve (MC) [6,7], which describes the temperature dependence of fracture toughness of ferritic steels, indexed by a material specific reference temperature, T_0. ASTM E 1921-97 [8] has recently standardised the process of evaluation of T_0 and the Master Curve under quasi-static loading conditions. However, its application to higher strain rates needs further verification/validation by dynamic fracture toughness evaluation. In this paper, the reference temperature, T_0, has been determined for the 9Cr-1Mo steel in a dynamic loading condition. A parallel effort has been made to evaluate T_0 with conventional Charpy (CVN) tests also. The Master Curve thus determined was compared with the RT_{NDT} based ASME K_{IR} curve. The results would enable evaluating the DBTT of 9Cr-1Mo steel in the light of dynamic fracture toughness.

2. MATERIAL AND T_0 DETERMINATION PROCEDURE

2.1. Material

The 20 mm thick plate of 9Cr-1Mo steel were supplied by M/s Creusot-Loire Industrie, France. The detailed chemical composition (in wt %) is given as C: 0.10, Cr: 8.44, Mo: 0.94, Ni: 0.17, Cu: 0.10, Si: 0.48, S: 0.002, P: 0.007, Al: 0.011, Fe: balance. The plate was normalised at 950 ^{O}C for 30 minutes and tempered at 750 ^{O}C for 60 minutes.

2.2. T_O^{dy} from Pre-Cracked Charpy Test (PCVN)

The dynamic fracture toughness (K_{Jd}) was determined from the pre-cracked Charpy test. To minimise the inertial oscillations effect on load determination, the initial T_0 was determined by tests conducted at a hammer velocity of ~1.12 m/s; this was further converted to T_0 at 5.12 m/s applying an test velocity dependent shift in T_0. ASTM E 1921 suggests that the test temperature should be selected such that it yields fracture toughness values (corresponding to 1" thickness specimens) close to 100 MPa√m. As per this guideline, following some trial and error tests, the test temperature was selected as –50 ^{O}C. The initial crack length was measured by a travelling microscope, using ten point averaging method. The test temperature, test velocity, validity of test results and 1" corrected K_{Jd} values are reported in Table. 1. Two tests have been conducted at a hammer velocity of 5.12 m/s, at –20 ^{O}C and the corresponding results are also shown in Table 1.

Table.1 K_{Jd} with validity limits and T_0 from the PCVN tests of 9Cr-1Mo steel.

Test Temp(^{O}C)	V_0, (m.s^{-1})	a_0 (mm)	K_{Jd} (MPa.√m)	σ_{yd} (Mpa)	Validity limit, (MPa.√m)	Validity results	K_{Jd} (1 inch) (MPa.√m)
–70	1.08	4.40	57.84	-	-	-	49.97
–55	1.06	4.42	56.38	-	-	-	48.82
–50	1.11	4.50	137.13	717.34	166.13	Valid	112.78
–50	1.11	4.39	162.26	707.60	166.64	Valid	132.68
–50	1.14	4.70	186.98	742.62	165.90	Invalid	152.21*
–50	1.15	4.38	83.528	713.61	167.53	Valid	70.32
–50	1.12	4.60	118.87	745.56	167.74	Valid	98.31
–50	1.14	4.54	P_F not clear	717	165.55	-	-
–50	1.10	4.60	243.87	721.56	165.16	Invalid	197.33*
–50	1.10	4.80	60.00	$P_F < P_{GY}$	-	Valid	51.70
–50	1.13	4.88	163.00	762.5	165.23	Valid	136.44
–50	1.10	5.09	70	$P_F < P_{GY}$	-	Valid	60
–50	1.12	4.63	133.95	712.10	163.60	Valid	110.26
–20	5.12	4.87	286.70	779.70	166.70	Invalid	230.57*
–20	5.12	4.62	296.50	789.20	171.60	Invalid	233.44*

The cumulative probability of failure, p_f, the scale parameter of the Weibull distribution, K_0 and the median K_{Jd} wwere calculated according to ASTM E 1921. The T_0^{dy} thus determined was –59.4 °C. The corresponding Weibull plot is shown in Fig. 1. A near slope four agreement has been observed in theWeibull plot.

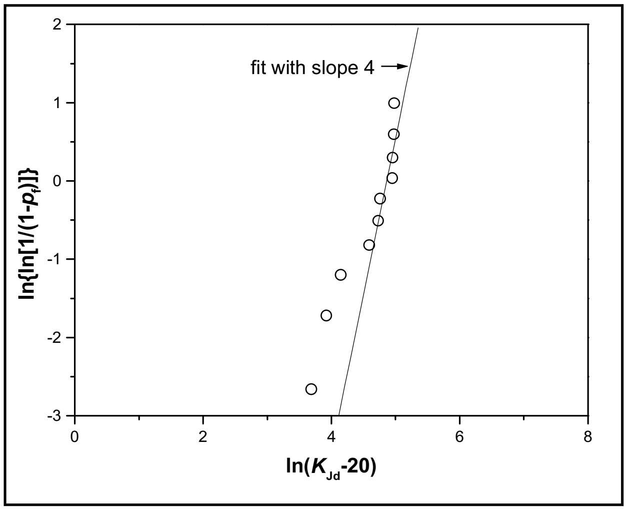

Figure 1. Weibull plot from the K_{Jd} data, obtained from PCVN tests.

To account for the test velocity effect on the reference temperature, T_0, amongst various equations proposed by Yoon *et al.*[9], the following represent the highest and the lowest values respectively:

For A515 steel, $T_0 = 6.1 \ln (dK/dt) - 18$ [1a]
For A533B weld, $T_0 = 2.7 \ln (dK/dt) - 87$ [1b]
dK/dt is the rate of change of stress intensity factor.

In a more generalised form, Schindler *et al.* [10] have proposed the following equation for the shift in T_0, associated with the change in test velocity or the stress intensity factor rate as:

$$\Delta T \cong (22 - 0.016\sigma_y)\log\frac{\dot{K}_{ref}}{\dot{K}_{test}} \cong (22 - 0.016\sigma_y)\log\frac{\dot{V}_{ref}}{\dot{V}_{test}} \qquad [2]$$

where σ_y is the yield stress at the test temperature/strain rate.

In the present campaign, the stress intensity factor rate estimated at ~1.12 m/s for the –50 °C tests yields a value of $2.754(\pm 0.254) \times 10^5$ MPa√m/s. From the two

PCVN specimens tested at 5.12 m/s, the stress intensity factor rate was estimated as ~ 10^6 MPa√m/s for the test velocity of 5.12 m/s. Applying these results in the Eqn. 1-a&b, for tests in 1.12 and 5.12 m/s, the T_0 yields a shift of 14 and 6.2 ^{O}C respectively. However, the Eqn. 2 shows a shift of ~ 7 ^{O}C based on the stress intensity based calculation and 7.5 ^{O}C based on velocity based estimation. It is important to mention here that the dynamic yield stress estimation from PCVN tests gives a higher value than that estimated from the Charpy V-notch tests at a particular temperature [11]. Here, the yield stress estimated from Charpy V notch tests, 660 MPa at –50 ^{O}C [15], has been used to arrive at a conservative estimate (higher ΔT) of shift.

From the above mentioned various estimates for the test velocity induced shits of T_0, it is observed that the Schindler,s velocity based estimation (Eqn. 2) is more tangible from a practical point of view and considering the scatter involved in all the test parameters in determining T_0, the result seem to be reasonable. So, the T_0^{dy} corresponding to test velocity of 5.12 m/s is estimated as –51.9 ^{O}C. The Master Curve at test velocity 5.12 m/s is plotted using T_0^{dy} as –52 ^{O}C.

2.3. T_O^{dy} from Charpy V-Notch Tests

T_0^{dy} from Charpy V-notch test was estimated from the K_{Jd} values at different temperatures. K_{Jd} values were estimated from the J_{Id}, where J_{Id} values had been evaluated from the load-displacement plots and the absorbed Charpy energy using Eqn. 3.

$$J_0 = \frac{7.33 \cdot n \cdot C_V \cdot 10^{-3}}{1 - 1.47 \cdot (\dfrac{C_V}{\sigma_{fd}})} \qquad [3]$$

The original equation has been proposed by Schindler [12] and later modified by Sreenivasan *et al* [13] where the work hardening exponent *n* was determined directly from the load-displacement diagram obtained from the instrumented Charpy V-notch tests alone.

The validity of the estimated K_{Jd} values were evaluated as per ASTM E 1921 procedure with a ligament length of 8 mm and subsequently were converted to 1” size equivalence. An exponential fit has been obtained through the 1” size corrected and valid K_{Jd} data and the T-K_{Jd} pairs between 80 to 120 MP√m were selected and analysed for evaluating the reference temperature using the multi-temperature equation proposed by Wallin [7]. This yields a T_0^{dy} of –30 ^{O}C. However, it yields a result of –47.3 ^{O}C if the fit incorporates all the invalid data also. The result shows a potential in determining dynamic reference temperature from the Charpy-V notch tests alone.

3. THE DYNAMIC MASTER CURVE

Using the reference temperature, T_0^{dy}, as -52 ^{O}C, the dynamic Master Curve corresponding to 5.12 m/s is constructed as per ASTM 1921 guideline. Fig. 2 shows the dynamic Master Curve with respect to the pre cracked test results and the ASME K_{IR} curve with $RT_{NDT} = -25$ ^{O}C [15]. According to the shift of 7.5 ^{O}C in T_0^{dy} at test velocity of 5.12 m/s with respect to the 1.12 m/s, the temperatures corresponding to the PCVN K_{Jd} results are also shifted by 7.5 ^{O}C. Fig. 2 also compares the trend in the K_{Jd} or K_{Id} values, obtained from the the Charpy-V and drop weight tests [14,15], with the dynamic Master Curve.

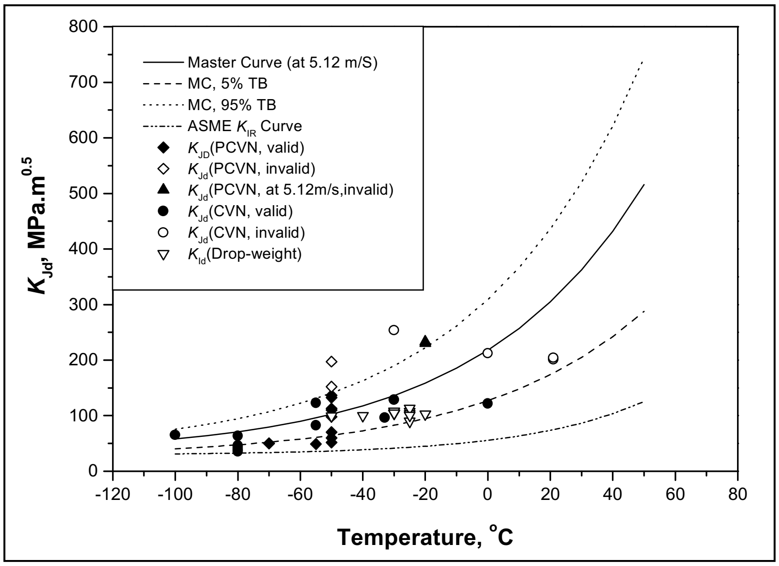

Figure 2. Master Curve (at 5.12 m/s) and K_{IR} curve for 9Cr-1Mo steel.

The trend in the K_{Jd} values obtained from the Charpy V-notch tests shows good agreement with the Master Curve; even the invalid values (except one) lie within the tolerance bound of the Master Curve. Thus, the T_0^{dy}, determined as -47.3 ^{O}C, incorporating all the valid and invalid data from the Charpy-V notch tests seems reasonable. Compared to the Master Curve, the ASME K_{IR} curve proves to be too conservative.

4. CONCLUSIONS

1. The T_0^{dy} determined for 9Cr-1Mo steel at a loading rate of 5.12 m/s is -52 ^{O}C where as the RT_{NDT} is determined as -25 ^{O}C.
2. ASME K_{IR}-curve approach proves to be too conservative compared to the real trend of the fracture toughness with temperature, as shown by the dynamic Master Curve.

3. The K_{Id} determined from the conventional Charpy V-notch tests and the drop-weight tests follow the trend shown by the dynamic Master Curve. The methodology suggested here for evaluating T_0^{dy} using only CVN test bears potential, but needs to be verified with other materials.

References:

1. Kohyama A., Hishinuma A., Gelles D.S., Klueh R.L., Dietz W. and Ehrlich K., *J. Nucl. Mater.*, **231-237** (1996) p. 138.
2. Hu N.L. and Gelles D.S., Influence of Radiation on Material Properties, ASTM, STP 956 (1987) p. 83.
3. ASME Boiler and Pressure Vessel Code, Section III, *Nuclear Power Plant Components*, Div. 1, Appendix G, ASME, New York (1980).
4. ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, Div.1, Appendix A, ASME, New York (1980).
5. Landes J. D. and Shaffer D. H., Scientific Paper 79-ID3-JINTF-P4; Pittsburgh, Pa, Westinghouse, 1979.
6. Wallin K., Saario T and Torroren K, *Metal Science*, **18** (1984) p.13.
7. Wallin K., *Advaces in Fracture Research (Proc. Int. Conf. Fracture, ICF-9)*, B.L. Karihaloo, Y.W. Mai, M.I. Ripley and R.O. Ritchie (Eds.), Sydney, Australia, Vol. 5 (1997) p.2333.
8. ASTM E 1921-97 *‘”Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range”*, ASTM, 1997.
9. Yoon K.K., Hall J.B., Van Der Sluys, Higuchi M and Lida K., The 2001 ASME Pressure Vessel and Piping Conference, July 23-26, Atlanta, Georgia, USA (2001) p.1.
10. Schindler H.J., Varga. T., Njo D.H. and Prantl G., Materials Aging and Component Life Extension, Vol. 2, V. Bicego, A. Nitta, R. Viswanathan [Eds.], Proc. of Int. Symp. on Mat. Ageing and Component Life Extension, Milan, Italy, 10-13 Oct. (1995) p.1367.
11. Sreenivasan P.R. and Mannan S.L., *Int. J. Fracture*, **101**(2000) p.229.
12. Schindler H.J., in *Pendulum Impact Testing: A Century of Progress*, ASTM STP 1380, American Society of Testing and Materials, West Conshohocken, PA, (2000) p.337.
13. Sreenivasan P.R., Shastry C.G., Mathew M.D., Rao K.B.S., Mannan S.L. and G. Bandyopadhyay, *J. Engng. Mat. And Tech. (Trans ASME*), **125** (2003) p.227.
14. Moitra A., Sreenivasan P.R., Ray S.K., Mannan S.L., *Int. J. Pres. Ves. & Piping*, **69** (1996) p. 253-261.
15. Moitra. A, Ph.D Thesis, submitted at Banaras Hindu University, Varanasi, 2003.