MASTER CURVE METHODOLOGY AND FRACTURE BEHAVIOUR OF THE CAST STEEL

M. Holzmann, V. Kozák, I. Dlouhý*

The methodology of master curve (MC) for the cast low carbon manganese steel is tested here. For determining the reference transition temperature, T_o, which is taken as a basic material characteristic positioning the MC on the temperature axis, the large (1T) specimen is required. Additionally, the small pre-cracked Charpy type specimens have been used for determining the fracture transition behaviour and for measurement of fracture toughness. After the size correction of results to 1T, using the weakest link theory and the local approach, the corrected results were also used for determining the T_o. The validity of MC concept for cast steel and the applicability of the small pre-crack specimens for the T_o determination is discussed.

INTRODUCTION

The methodology of master curve (MC) [1] is currently widely used for transition behaviour evaluation of fracture toughness. The verification of this concept has been performed for steel of pressure vessel and weldments [2-7]. For determining the reference transition temperature, T_o , which is taken as a basic material characteristic localising the MC on the temperature axis, the large (1T) specimens are required. But there are structures (plants) under operation for which transition behaviour of fracture toughness is of great interest (reactor pressure vessels technology, rotors etc.) and application of MC concept would be very useful here. However for these components only small specimens (Charpy V-notch) can be used for assessment of degradation. The effort is now concentrated on application of pre-cracked small specimens for these purpose [8]. Some works, mainly of Wallin [7,9], have shown that the small pre-cracked specimens can be used in determining reference temperature, T_o and thereby making possible to apply MC concept for the integrity assessment procedure of these components.

- The Institute of Physics of Materials, Žižkova 22, 616 62 Brno, The Czech Republic

In the present paper, the MC concept has been used for assessment of the fracture toughness transition behaviour of C-Mn cast steel intended for fabrication of large container for spent nuclear fuel. Small pre-cracked specimens and 1T SENB specimens were used to measure fracture toughness over wide temperature range. Using the results obtained the reference transition temperatures, T_o, were determined for both type of specimens and compared each other. Having the T_o, the MC may be drawn. Its validity for the cast steel is discussed. Additionally, the prediction of the fracture toughness scatter of large (1T) specimens through that ones small pre-cracked using Weibull stress concept has been also performed.

MATERIAL CHARACTERISTRICS AND EXPERIMENTS

A manganese cast steel has been utilised for experiments having chemical composition in wt %:0.09C, 1.18Mn,0.37Si, 0.01P, 0.025S, 0.12Cr, 0.29Ni, 0.29Cu, 0.03Mo, 0.028Al. The material has been supplied by Škoda company as a component part produced for attest of the container of nuclear spent fuel.

True stress-strain curves have been measured using cylindrical specimens with diameter of 6 mm being loaded over temperature range –196°C to -60°C at cross-head speed of 2 mm.min^{-1}. Standard FEA – ABAQUS 5.7 was used to model elastoplastic behaviour for tensile notched specimens. In all cases the multilinear model was used.

Fracture toughness were measured using standard 25 mm thick specimen loaded in the 3-point bending with a/W ratio of 0.5. Small pre-cracked Charpy type specimens have been also tested in the same temperature range. For one selected temperature in lower shelf region (below temperature t_{GY} at which coincidence of F_{FR} and F_{GY} on their temperature dependencies) a range of round tensile notched bars were tested to obtain data for statistical local approach procedure treatment. Charpy type specimens were tested under the two types of loading: (i) CVN impact energies were measured using instrumented impact tester over a temperature range of –90°C to 25°C; (ii) CVN specimen were tested in static 3-point bending over temperature range –180°C to –50°C.

Accepting the Beremin approach to the analysis of local criteria for cleavage fracture the location and shape parameters were calculated using FEM for notched tensile bars. Prediction calculated for cell sizes given data fully comparable with experimental values. Different size of process zone has no influence on computed local parameters. Values used for the MC computations are: $m = 56$, $\sigma_U = 1820$ MPa ($V_o = (1.e\text{-}6)^3$ m).

RESULTS AND DISCUSSION

Fracture behaviour of 1T SENB specimens

On the basis of preliminary measurement of the fracture toughness using this type of specimen the temperature of –100 °C has been chosen for determining the reference temperature T_o . Six SENB specimens were used to measure the fracture toughnesses at this temperature. The K_{Jc} results obtained are given in Table 1. Using relationship [1]:

$$K_O = [\sum_{i=1}^{N}(K_{Jc(i)} - K_{\min})/(r-0.3068)]^{1/4} + K_{\min} \qquad (1)$$

where $K_{\min} = 20$ MPam$^{1/2}$, one gets for K_o the value $K_o = 79.2$ MPam$^{1/2}$. $K_{Jc(med)}$ is given by: (2)

$$K_{Jc(med)} = (K_o - K_{\min})[\ln(2)]^{1/4} + K_{\min}$$

After substituting K_o and $K_{\min}$ the value of $K_{Jc(med)} = 74$ MPam$^{1/2}$. Finally, utilising the equation:

$$T_o = T - \frac{1}{0.019}\ln[\frac{K_{JC(med)} - 30}{70}] \qquad (3)$$

the reference temperature T_o may be established $T_o = -76$ °C.
The master curve for C-Mn cast steel investigated is described by:

$$K_{Jc(med)} = 30 + 70\exp[0.019(T + 76)] \qquad (4)$$

Figure 1 shows the master curve together with the tolerance bounds 5% and 95%.

In this diagram the measured values of fracture toughness in temperature range – 100 to – 40 °C are plotted. Full point represent data keeping values [1]:

$$\frac{b\,\mathrm{Re}}{J_C} = 30 \qquad (5)$$

Some peculiarities of fracture behaviour of C-Mn cast steel follow from the Figure.

- Only for the fracture toughness values being below $T_o + 15$ °C the master curve methodology may be used to predict the fracture toughness behaviour.
- At the temperature $T_o + 26$ °C the sharp transition of fracture toughness to much higher of K_{Jc} occurs. It must be emphasised that for those specimens having this high values of K_{Jc}. The fracture was initiated by cleavage indicating that the C-Mn cast steel has large intrinsic resistance against ductile tearing. The left side of Eq. (5) for the specimen with high values of K_{Jc} equals to 18 indicating a large loss of constraint at MC at onset of fracture initiation. This phenomenon might be connected with tensile stress-strain curve, which exhibits large yield plateau; so representing no hardening material. This behaviour may play the role at higher temperature, where at the low yield stress the local peak stress ahead the crack front is small. The phenomenon is being now under examination.

Fracture behaviour of small pre-cracked Charpy specimen

The temperature dependence of fracture toughness is given in Figure 2. Data plotted by full points meet the validity condition (5). Only these data were size corrected to 1T thickness. The weakest link theory has been used in the expression [1]:

$$K_{Jc(1T)} = 20 + (K_{Jc(10)} - 20)(\frac{B_{10}}{B_{1T}}) \qquad (6)$$

The corrected data are plotted in Fig. 3, in which MC $K_{Jc(med)}$ and tolerance boundaries for 5 and 95 % are replotted. As seen, corrected data, especially at –100°C, lie above $K_{Jc(95)}$ tolerance bound. It seems to be possible that validity condition, Eq. (5) is not striate enough for small pre-cracked specimens. Koppenhoefer and Dodds [11] have shown, using the Weibull stress concept, that the value on right side of Eq. (5) should be much greater to maintain the high constraint in small pre-cracked specimens.

Additionally, an attempt has been made to establish to establish the reference temperature T_o utilising the corrected fracture toughness values at –100°C. The measured values $J_{C(10)}$, $K_{Jc(10)}$ and size corrected values $J_{C(1T)}$, $K_{Jc(1T)}$ are listed in Table 2. For size correction two methods have been used:

-the weakest link theory, Eq. (6);

-the Weibull stress concept [10].

In former case, the T_o was determined by means of Eqs. (1), (2) giving T_o = -100°C, that is by about 24 °C lower than T_o established using 1T SENB specimens. In the latter case the size correction has been performed employing the Weibull stress concept [10]. The procedure has been as follows. After determining the local parameters, as is mentioned in the beginning of the paper, it is important to compute variation σ_w as a function of J integral for both types of specimens. Then from a given value of J integral in pre-cracked Charpy specimen it is necessary to find its corresponding σ_w. This value have to be transfer into the diagram for 1T SENB specimen. Having used the corrected data, calculating the average values $K_{Jc(mean)}$ and substituting this into Eq.(3) one gets T_o = 90 °C. This is value being nearest on the T_o established by means of 1T SENB specimens.

CONCLUSION

The main conclusions are as follow:

- MC concept was shown to be valid in the lower transition range for C-Mn cast steel.
- Fracture toughness was measured using small pre-cracked Charpy specimens and results were corrected to the 1T SENB specimens.
- Reference temperature T_o determined from size corrected results was little different from T_o evaluated using 1T SENB.

ACKNOWLEDGEMENTS

This research was financially supported by grant No. 101/97/1045 of the Grant Agency of the Czech Republic.

TABLE 1 – $K_{JC(1T)}$ at –100 °C.

Rank	$K_{JC(1T)}$ [MPa m$^{1/2}$]
1	58.1
2	63.4
3	70.3
4	83.5
5	84.3
6	90.5

TABLE 2 - The measured and corrected fracture toughness values at –100 °C.

$K_{JC(10)}$ [MPa m$^{1/2}$]	$K_{JC(1T)}$ 1 [MPa m$^{1/2}$]	$J_{JC(1T)}$ 1 [MPa m]	$J_{JC(1T)}$ 2 [MPa m]	$K_{JC(1T)}$ 2 [MPa m$^{1/2}$]
99.3	83.0	0.029	0.0244	74.4
104.5	87.2	0.033	0.0266	78.3
129.7	107.2	0.0497	0.0325	85.9
136.7	112.8	0.055	0.0375	92.4
140.9	116.1	0.0584	0.0381	93.7
144.6	119.0	0.0613	0.0432	99.6
			0.0501	107.4

1 corrected using weakest link teory; 2 corrected using Weibull stress concept;

REFERENCES

(1) Test Method For the Determination of Reference Temper., T_o, for Ferritic Steels in the Transition range, ASTM, Draft 15, rev. 6-13-97.

(2) K. K. Yoon, J. Pressure Vessel Technology, Vol. 117, 1995, pp. 378.-382.

(3) D. Aurich, B. Jaemicke, H. Veith, Safety and Reliability of Plant Technology, 22. MPA Seminar, October, 1996, paper 21.

(4) M. Holzmann, I. Dlouhý, Zváranie, Vol. 46, 1997, pp. 219-224, (in Czech).

(5) R.E. Link, J. A. Joyce, In Constraint Efect in Fracture, ASTM STP 1244, Eds. M . Kirk, Ad. Bakkers, 1995, pp.286-315, Philadelphia USA.

(6) D. E. McCabe, M. A. Sokolov, R. K. Nansland, In Struct. Mechanics in Reactor Technology, 14 Int. Confer., Vol. 4, division G, Lyon, France, 1997, pp. 349-356.

(7) K. Wallin, In Advances in Fracture Research, ICF 9, Eds. B. L. Kari Haloo, Y. W. Mai,M.I. Ritchie, 1997, Pergamon, Amsterdam, pp. 2333-2344.

(8) M. E. Mayfield, M. G. Vassilaros, E. M. Hacket, M. A. Mitchel, K. R. Wichman , J. R. Strosnider, L. C. Shao, Ibid as [5], pp. 17-29.

(9) K. Wallin, Validity od Small Specimen Fracture Toughness Estimates Neglecting Constrain Correction, Ibid as [4], pp. 519-537.

(10) Beremin, F.M.: Metal. Trans. A, Vol. 14A, pp. 2277-2287, 1983.

(11) K.C. Koppenhoefer, R. H. Dodds, Eng. Fract. Mech., Vol 58, 1997, pp. 224 – 270.

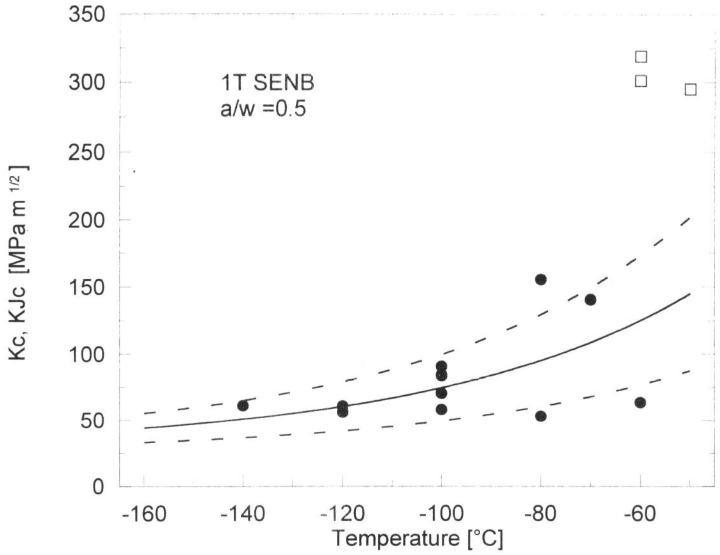

Figure 1 Fracture toughness versus temperature

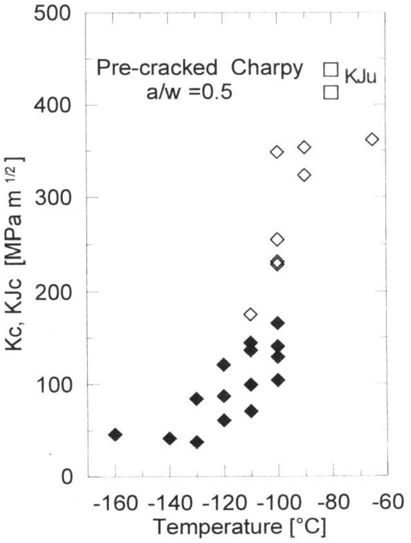

Figure 2 Fracture toughness versus temperature

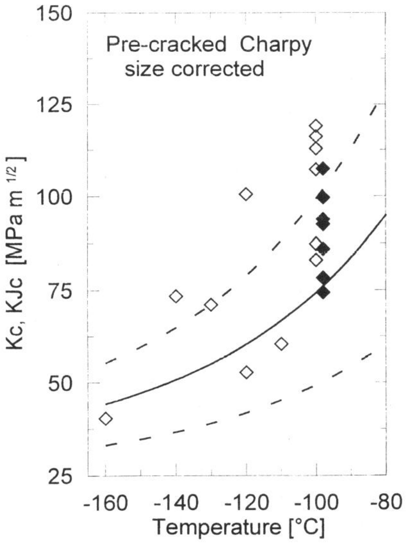

Figure 3 Corrected fracture versus temperature