PVP-Vol. 393, Fracture, Fatigue and Weld Residual Stress
ASME 1999

ACCURACY IN THE T_o DETERMINATION: NUMERICAL VERSUS EXPERIMENTAL RESULTS

Carlos A. J. Miranda and Arnaldo H. P. Andrade
IPEN-CNEN/SP
San Paulo, Brazil

John D. Landes
University of Tennessee
Knoxville, Tennessee, USA

Donald E. McCabe and Ronald L. Swain
Oak Ridge National Laboratory
Oak Ridge, Tennessee, USA

ABSTRACT

The characterization of transition fracture toughness using the Master Curve concept with T_o has been proven to work well for a wide range of ferritic steels. However, the validity of the reference temperature (T_o) determination using the toughness values obtained from small specimens is still a concern among researchers, principally when toughness results are obtained using Charpy specimens. Due to their reduced level of constraint, they should be tested in the lower portion of the transition region, where the uncertainties are great due to a relatively flat Master Curve.

This work presents some experimental toughness results, obtained with an A508 Class 3 steel, using specimens smaller than the unit size. The test matrix contains 59 specimens at four temperatures. Two sets of twelve ½T C(T) specimens each were tested at -100 °C and at -75 °C. These two sets gave almost the same T_o value and are used as reference for the comparison with the toughness results from the other geometries: the "regular" 10mm x 10mm pre-cracked Charpy specimen and SE(B) specimens with a 9mm x 18mm cross-section. The ability of small bend specimens to give reproducible T_o values, the validity of the use of small specimens, and the best temperature range for testing are also discussed.

INTRODUCTION

The Master Curve Method was developed by Wallin (1991a, b) and can be used to describe the entire toughness versus temperature behavior for ferritic steels in the transition fracture region. It is based on the reference temperature (T_o) determination from just one set of toughness values measured in a given temperature (T). A recent study involving many heats of ferritic steels (Kirk and Lott, 1998) shows that the Master Curve fits well for a wide range of ferritic steels in the transition region. This Master Curve method was adopted by the ASTM, standard E1921-97 (1997), to determine the T_o value for ferritic steels in the transition region. By this standard, the minimum number of valid experimental results in the data set, for a given temperature T, should be six. Eq. (1) gives the size criterion for a measured toughness value, expressed as K_{Jc}, to be valid (E and σ_{ys} are the material elastic modulus and its yield stress, b_o is the remaining ligament of the specimen).

$$K_{Jc,\lim it} \leq \sqrt{\frac{E\,\sigma_{ys}\,b_o}{M}} \qquad (1)$$

The M value of Eq. (1) was set to 30 to limit the small specimen size effect that introduces error between near crack tip (local J) and far-field J that is measured in experiment (Ruggieri et al., 1998). So, indirectly this size criterion imposes an upper limit in the test temperature that depends on the geometry and the material.

All results are referred to a unit size (1T: W = 50.8 mm, B = 25.4 mm) suggesting that this is a recommended test size. A weakest-link thickness correction should be applied to the obtained toughness values when the tested specimens have a different thickness.

The reliability in the reference temperature (T_o) determination using the toughness values obtained from specimens smaller than this unit size is still a concern among researchers (McCabe, 1998), principally those toughness results obtained using Charpy specimens and their sub-sized versions. Due to the reduced level of constraint in these small specimens, and to satisfy eq. (1), they should be tested in the lower portion of the transition region, where the uncertainties are greater due to being in a relatively flat part of the Master Curve.

In a previous work (Miranda and Landes, 1998) a method was shown to determine the confidence level in the T_o determination, as a function of the number of valid results and the test temperature. The work does not take into consideration the geometry from which the toughness values were obtained. From Miranda and Landes (1998) it can be seen that by using 6 specimens, or six valid results, one can get about 90% of confidence when the test temperature (T) is the same of the reference temperature T_o (i.e.: $T-T_o = 0$ °C). For the same test temperature we need about 15 valid results to have 98% of confidence in the T_o determination, i.e.: the obtained T_o falls within an interval of +/- 10 °C of the true T_o.

This work presents some experimental T_o determinations obtained for an A508 Class 3 steel using specimens smaller than the unit size. The validity of the use of small specimens, like the pre-cracked Charpy specimen (B=W=10mm) or bend bars, with B=9mm and W=18mm, and the accuracy of the obtained reference temperature, T_o, are discussed in this paper. The best temperature range for testing small specimens is also discussed.

TEST MATRIX

A heat of an A508 Class 3 steel was used to obtain three plates with dimensions of about 1500mm x 1000mm x 130mm (length, width, and thickness) each. A piece was taken from one of these plates to machine the fracture mechanics specimens used in this work. All of the specimens were machined in the L-T orientation and they were taken from the full thickness of the plate. This includes 0.5T C(T), Charpy size and 0.354T SE(B) specimens with nominal a/W = 0.6, 0.5, and 0.5 respectively. The test matrix (type, number of specimens and test temperature) is presented in Table 1 along with some other information.

A test temperature of -106°C was chosen to allow a direct comparison with toughness values obtained previously for the same heat of this A508 steel (Aquino, 1997). These previous toughness results, using mostly pre-cracked Charpy specimens tested at -106°C and -120°C show that there is no significant influence of the orientation on the toughness. From the measured toughness values presented by Aquino (1997), the average reference temperature value should be around -115°C. These toughness results, including those results obtained with six SE(B) specimens tested a -106°C, will, also, be used in the discussion in this paper.

OBTAINED TOUGHNESS RESULTS

The first group of results was obtained using two sets of 12 ½T C(T) specimens tested at -100°C and -75°C, and three sets of 6 pre-cracked Charpy specimens tested at -106°C, -90°C and -75°C. Some of the Master Curve parameters (K_o, T_o, etc) are presented in Table 1. To obtain these parameters the ASTM E1921-97 standard procedure (ASTM, 1997) was applied. The toughness values, normalized to 1T thickness, and the Master Curve with the associated 5% and 95% of confidence bound curves are presented in Figure 1. Data sets tested at the same temperature are presented with a horizontal shift for clarity purposes.

No stable crack growth was observed in any specimen tested at -106 °C, -100 °C, and -90°C. Less than 0.1mm of stable crack growth was observed in some of the Charpy specimens tested at -75°C. The average value determined by testing C(T) specimens (T_o = -92.7°C) will be considered as the reference temperature value for this material.

From eq. (1), the $K_{Jc,limit}$ for the ½T C(T) and the Charpy specimens are about 200 and 140 MPa√m, respectively. Accordingly, all C(T) results but one obtained at -75°C are valid. This shows that it would be possible to test at a higher temperature using this geometry and still obtain valid results for T_o determination. Due to the exponential nature of the Master Curve this higher test temperature for this geometry should be not far from -70°C., i.e: $(T-T_o)_{max} \approx 22$°C. All Charpy results obtained at -106°C and at -90°C are valid, and just one of six Charpy result obtained at -75°C is valid. This shows that for this type of geometry the highest reasonable test temperature for Charpy specimens is around -90°C, i.e: $(T-T_o)_{max} \approx 0$°C and, so, it is not possible to test Charpys at a temperature much higher than T_o.

The set of Charpy results obtained at -90°C has a median value slightly lower than the median value that comes from the group obtained at -106°C. Despite the fact that all toughness values are valid for T_o determination, this is an unusual behavior, different from the expected one. It is due to a combination of the experimental and statistical uncertainties and the material variability. The influence of these factors is stronger as the number of specimens is reduced.

Due to this fact it was decided to test five remaining Charpy specimens at -90°C. This additional work will be done in a near future. In doing this the confidence in the T_o determination, at -90°C, will increase from about 84% (6 specimens) to about 95% (11 specimens) assuming that all new values will be valid ones for T_o determination (Miranda and Landes, 1998).

The second group of results, using two sets of SE(B) specimens, normalized for 1T thickness, is presented also in Figure 1. The other parameters related with T_o calculation are presented in Table 1. The tests were performed at -106°C (8 specimens) and at -75°C (9 specimens). Again, no stable crack growth was observed in the specimens tested at -106°C, and just one specimen tested at -75°C had a small amount of stable crack growth (<0.1mm).

The $K_{Jc,limit}$ value for these SE(B) specimens is about 190 MPa√m. Therefore all toughness values obtained at -106°C are valid, and just 3 values at -75°C are valid for T_o determination. There are 3 other values very near this $K_{Jc,limit}$ value. This shows the possibility to obtaining the minimum number of valid results at -75°C by increasing the number of test specimens. However, it seems that this temperature is, for this geometry, an upper limit i.e: $(T-T_o)_{max} \approx 20$ °C and, so that it is not possible to test at higher temperatures to obtain T_o with this geometry (SE(B), B=9mm, W=18mm).

Previous Results

In a previous study, conducted by Aquino (1997) using the same heat of material, 34 'regular' pre-cracked Charpy specimens (10mm x 10mm) and 6 SE(B) specimens with B = 9 mm and W = 18 mm were tested for toughness measurements. Figure 2 shows them as corrected to 1T thickness in graphical form. The sets at the same temperature are presented with a shift for clarity purposes. Some other parameters are presented in Table 2 along with the T_o values.

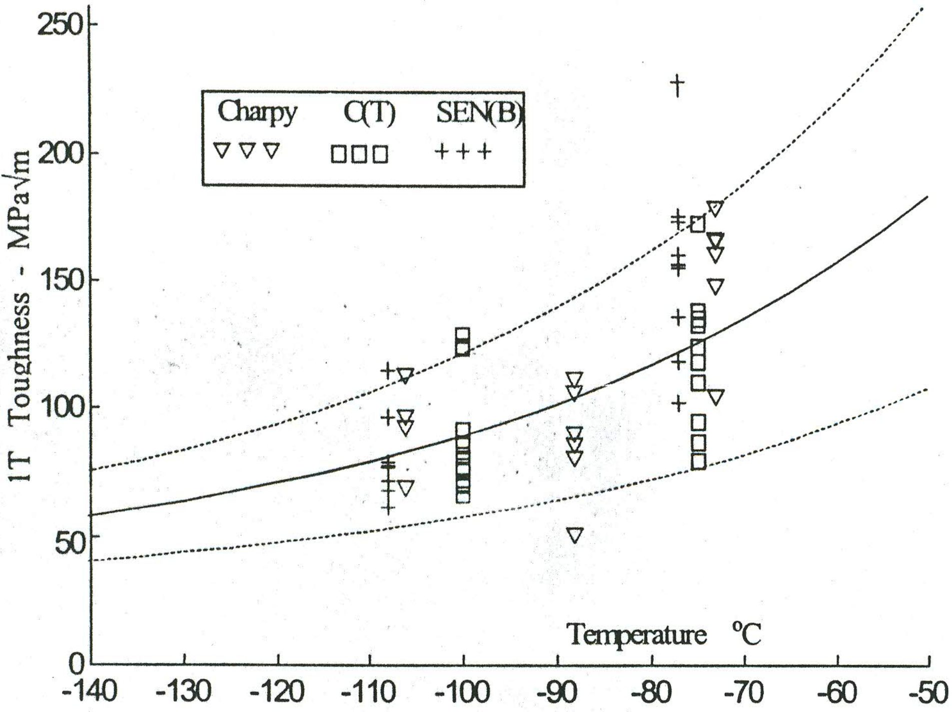

Figure 1: Master Curve with the 5% and 95% bounds and the toughness results (transformed to 1T values)

Table 1: Test matrix and Master Curve parameters

Geometry	Test Temperature	# Specimens / Valid Results	Master Curve Parameters			Average
			$K_{Jc,median}$ [1]	K_o [1]	T_o	T_o
	°C	-----	MPa√m		°C	
CT	-75	12 / 11	124.4	134.4	-90.7	**-92.7**
	-100	12 / 12	93.4	100.5	-94.8	
Charpy	-75	6 / 1	165.1	179.1	[-109.6][2]	-----
	-90	6 / 6	89.3	96.0	-81.3	-90.4
	-106	6 / 6	91.8	98.7	-99.4	
SE(B)	-75	9 / 3	172.1	186.7	[-112.2][2]	------
	-106	8 / 8	82.1	88.1	-90.5	-90.5
Overall T_o average value						-91.2

[1] – after thickness adjustment; [ ][2] – Not a good / valid value according to E1921-97

In his work Aquino (1997) assumed: σ_{ys} = 550 MPa at -106°C and σ_{ys} = 600 MPa at -120°C for this material. These same values were assumed in the present work. All specimens have nominal a/W = 0.5. No crack growth information was reported. The toughness results obtained were presented in a table format.

Two SE(B) specimens were tested at each orientation (T-L, L-T and S-T). At -106°C two sets of six Charpy specimens each were tested: one set for the T-L orientation and another set for the L-T orientation. At -120°C six Charpy for the T-L direction, six for the S-T direction and 10 Charpy for the L-T direction were tested.

Table 2: Previous results (Aquino, 1997)

Geometry	Test Temperature	# Specimens / Valid Results	Master Curve Parameters			Average
			$K_{Jc,median}$[1]	K_o[1]	T_o	T_o
	°C	-----	MPa√m		°C	
Charpy	-106	12 / 7	117.	126.	-117.	-116.
	-120	22 / 19	94.	101.	-115.	
SE(B)	-106	6 / 4	142.	153.	[-131][2]	------
			Overall T_o average value			-116.

[1] – After thickness adjustment; [ ][2] – Not a good / valid value according to E1921-97

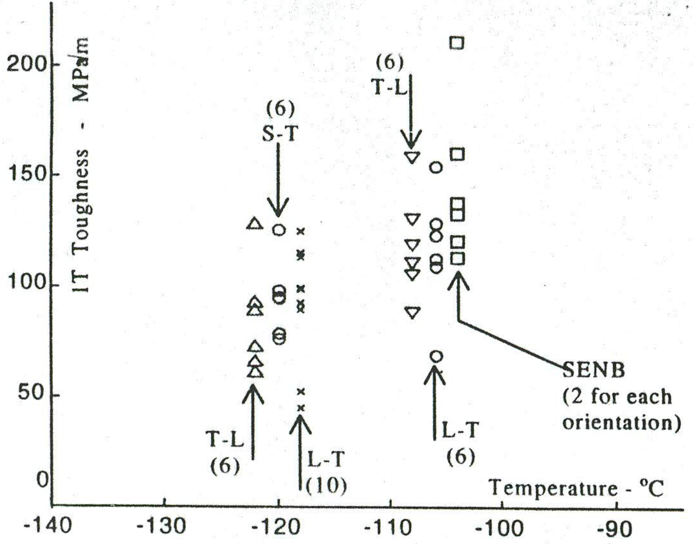

Figure 2: Previous results obtained for Charpy and SE(B) specimens tested at -120°C and at -106°C (Aquino, 1997).

At -106°C there are 7 valid Charpy toughness results from 12 tested and there are 19 valid from 22 tested at -120°C. So at both temperatures there are sufficient toughness values to perform the determination of the reference temperature. Among the six SE(B) specimens tested at -106°C there are only 4 valid toughness values. So the T_o value obtained from the SE(B) results is not a valid value. However T_o was calculated and shown in Table 2 only for comparison and completeness purposes.

The average T_o value that came from these results (-116°C, table 2) is almost 25°C lower than the average value obtained in the present work (-91.2°C, Table 1). One explanation for this difference can be the plate from which the specimens were taken. The reason for this difference is under investigation.

DISCUSSION

For the T_o determination, all ½T C(T) toughness values, but one, were valid. The two sets tested at -100°C and -75°C, with 12 specimens each, gave almost the same T_o value, within +/- 2°C from its average value. The 8 SE(B) specimens (8 valid results), tested at -106°C gave a T_o = -90.5°C. A value very near the obtained one using the C(T) results. The two sets of 6 Charpy results (6 valid) gave the largest T_o scatter: -81.3°C (at -90°C) and -99.4°C (at -106°C). Its average T_o value (-90.4°C) is very near the overall average T_o (-91.2°C).

Maximum Test Temperature

(1) *CT* - Considering this overall average T_o value, or the average T_o value that comes from the ½T C(T), as the reference temperature for this material, the toughness results obtained in this study show that it is possible to have a very reliable reference temperature value by testing the ½T C(T) specimens at temperatures a little higher than -75°C. That is: $(T-T_o)_{max} \approx$ 22°C.

(2) *Charpy* - Considering the behavior observed in the toughness results obtained with the Charpy specimens at -90°C, it can be expected that higher toughness values will be obtained when additional Charpy sized specimens are tested at this temperature. For the Charpy geometry the limit temperature seems to be at -90°C, or $(T-T_o)_{max} \approx$ 0°C.

(3) *SE(B)* - Using SE(B) specimens with B=9mm and W=18mm the maximum test temperature to obtain valid results for T_o determination seems to be around -75°C, so at $(T-T_o)_{max} \approx$ 17°C.

This work does not investigate the lower temperature ($T-T_o < 0$ °C) range. However, from a previous work, using numerical simulation (Miranda and Landes, 1998), it was shown that, due to the flat Master Curve in the lower transition region it is not advisable to test at $(T-T_o) < -25$°C. So, for this material, the best test temperature range to measure toughness for T_o calculation, using small specimens is -25°C < $(T-T_o)$ < 20°C for the ½T C(T) and 0.354T SE(B), and -25°C < $(T-T_o)$ < 0°C for the 'regular' (B=W=10mm) pre-cracked Charpy specimen.

CONCLUSIONS

Some toughness results were measured using sub-sized specimens: ½T C(T), 0.354T SE(B), and pre-cracked Charpy (0.394T, B=W) specimens. The results showed that, with the severe limitations on the upper limit of the test temperature (T) imposed by E1921, it is possible to obtain reliable values of the reference temperature (T_0) using sub-sized specimens. The best test temperature range to measure toughness to obtain the reference temperature for this material was determined.

ACKNOWLEDGEMENTS

The first author would like to thank the support that was given him by the Brazilian research agency CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) through the process 200.681/97-4(nv) and by the Brazilian Nuclear Regulatory Agency CNEN (Comissão Nacional de Energia Nuclear). This work was performed during his split scholarship program, at the University of Tennessee at Knoxville, TN, USA, as part of his PhD program. He would like also to thank Dr. R. Nanstad, Oak Ridge National Laboratory, who arranged for admittance and for use of laboratory equipment, and to R. L. Swain who guided the testing work.

REFERENCES

Wallin, K., 1991, "Fracture Toughness Transition Curve Shape for Ferritic Structural Steels," Proceedings of the Joint FEFG/ICF International Conference on Fracture of Engineering Materials, Singapore, August 6-8, 1991, pp. 83-88.

Wallin, K., 1991, "Statistical Modeling of Fracture in the Ductile-to-Brittle Transition Region," Defects Assessment in Components – Fundamentals and Applications, ESIS/EGF9, Ed. By J. G. Blauel and K. H. Schwalbe, Mechanical Engineering Publications, London, pp. 415-445.

Kirk, M. T., Lott, R., 1998, "Empirical Validation of the Master Curve for Irradiated and Un-Irradiated Reactor Pressure Vessels," Joint ASME/JSME Pressure Vessel and Piping Conference, July 27-30, San Diego, CA, USA.

ASTM, 1997, "Test Method for Determination of the Reference Temperature, T_0, for Ferritic Steels in the Transition Range", ASTM E1921-97, American Society for Testing and Materials.

McCabe, D. E., 1998, "Outstanding Issues for Future Research Activities in Ductile-Brittle Fracture," NSWC/USNA Workshop on Fracture in the Ductile-Brittle Fracture Transition, July 14-15, US Naval Academy, Annapolis, MD.

Miranda, C. A. and Landes, J. D., 1998, "Defining The Confidence Level in The Reference Temperature Determination", submitted to *Engineering Fracture Mechanics*.

Aquino, C. T. E., 1997, "An Approach to the Fracture Toughness Variation in the Ductile-Brittle Transition for Nuclear Pressure Vessel Steels" (in Portuguese), doctoral thesis, IPEN/USP, São Paulo, Brazil.

C. Ruggieri, R. H. Dodds Jr, and K. Wallin, 1998, "Constraint Effects on Reference Temperature, T_o, for Ferritic Steels in the Transition Region," *Engineering Fracture Mechanics*, Vol. 60, No. 1, pp. 19-36.