NOVEL CHARPY-FRACTURE TOUGHNESS CORRELATIONS FOR PREDICTING REFERENCE TEMPERATURE AND MASTER CURVE

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ABSTRACT

A correlation of reference temperature, T_0 with $T_{0\mathrm{Sch}}{}^{\mathrm{dy}}$ had been proposed by the authors earlier, where $T_{0\mathrm{Sch}}{}^{\mathrm{dy}}$ is the reference temperature corresponding to a median K_{Id} = 100 MPa√m evaluated by the ASTM E1921 procedure applied to K_{Id} vs T data, and K_{Id} has been calculated from instrumented CVN impact test data using modified Schindler relations. This paper applies the above method to some new results from the literature. In addition, a new correlation has been obtained that relates the micro-cleavage fracture stress, s_{f}, to the static Master Curve (MC) and T_0 based on a knowledge of variation of dynamic yield stress, s_{yd}, with temperature, both of which are obtainable from instrumented CVN impact tests. This new methodology has been applied to four steels and the prediction of T_0 and MC are satisfactory when compared to other correlations. The methods seem to be promising and need validation based on more extensive and complete data set.

Key Words: Master Curve, ASTM E 1921, reference temperature, micro-cleavage fracture stress instrumented Charpy test, fracture toughness, transition temperature, reactor pressure vessel

1. INTRODUCTION

Reactor pressure vessel (RPV) steels are increasingly being characterised in terms of the reference temperature T_0 and Master Curve (MC) as per the ASTM E-1921 standard [1]. The present authors [2] had earlier proposed a correlation of T_0 with $T_{0\mathrm{Sch}}{}^{\mathrm{dy}}$, where $T_{0\mathrm{Sch}}{}^{\mathrm{dy}}$ is the reference temperature corresponding to a median K_{Id} = 100 MPa√m evaluated by the ASTM E1921 procedure applied to K_{Id} vs T data and K_{Id} has been calculated from instrumented CVN impact test data using modified relations of Schindler's (modified Schindler relations). In this paper, the above correlation (Procedure-I) has been applied to some newer results from the literature. In addition, a new correlation (Procedure-II) has been obtained that relates the micro-cleavage fracture stress, s_{f}, to the static Master Curve (MC) and T_0 based on a knowledge of variation of dynamic yield stress, s_{yd}, with temperature, both of which are obtainable from instrumented CVN impact tests. Simply stated, based on a limited data set of T_0 and load-temperature diagrams for 4 steels [3,4], functional relations have been established between $s_{\mathrm{f}}/s_{\mathrm{yd}}$ and static MC fracture toughness data and constants of the functional relations are found to be related to $s_{\mathrm{f}}/s_{\mathrm{ys}}$(RT) (where s_{ys}(RT) is the RT-room temperature- static yield stress). This new methodology has been applied to some high alloy Cr-Mo bainitic or martensitic steels and the prediction of T_0 and MC are satisfactory when compared to other correlations. The methods seem to be promising and need validation based on more extensive and complete data set. Since the above procedures depend only instrumented CVN data, they will be less costly to apply (no precracking is necessary) and will also obviate the difficulties associated with determining $T_0{}^{\mathrm{dy}}$ from precracked CVN testing (because of severe size limitations, associated scatter and signal oscillations from the mechanics of the test, there needs to be precise control over test temperatures and test velocity for obtaining valid data from limited number of specimens).

2. MATERIALS AND DATA

The T_0 and instrumented impact test data for three steels (all similar to ASTM A533B-1 Type steels and referred as JRQ, Steel A, and Steel B [3,2]) and the instrumented CVN and K_{IC} data for a 2.25Cr1Mo steel (referred as 21Holz) [4] are used as basic data for developing the new correlation. This new methodology has been applied to a 9Cr-1Mo steel (referred as 91IGCBM) [5]; also, to a 9Cr1Mo steel weld (referred as 91WldIGC) , a 403 martensitic SS (referred as 403SS-IGC) and a service exposed 2.25Cr1Mo steel (referred as 21IGC) [2]. In addition, Procedure-I has been applied to a Mn, Mo, Ni pressure vessel steel of SA 503 Gr.3 Type in thee grain sizes: referred as A1, A2 and A3 [6]; and, also, to a 0.05C medium strength Ni, Cr, Mo steel (Steel5) and a 0.11C high strength Ni, Cr, Mo steel (Steel7) [7] and to two other ASTM A533B Cl.1 steels: BARC-JRQ and BARC-JPG [8]. The RT yield strength data and other reported transition properties for the various steels investigated are reported in Table 1. The relevant references may be consulted for complete details on the materials and welds.

Table 1 Reference and transition temperatures for various steels

Material [Reference]	RT_{NDT}, °C	T_{0Sch}^{dy}(°C)	T_0, °C	T_{28J}, °C	T_{41J}, °C	T_{68J}, °C	FATT, °C	s_{ys}/ MPa (RT YS)	T_0 from T_{0Sch}^{dy}/°C
Steel-B [3,2]	-45	**-35.6**	-97	-68	-61	-50	-32	462	**-95.2**
Steel-A [3,2]	-35	**0**	-67	-54	-42	-23	-4.4	469	**-76.2**
JRQ [3,2]	-15	**14.2**	-66	-37	-25	-6	25.4	488	**-68.6**
91IGCBM [2]	-25	**~-40**						**500**	**-97.5**
403SS-IGC [2]	32	**76.3**	--	22	34.5	60	--	**600**	**-35.4**
91WldIGC [2]	-4	**56**	--	-3	8	24	--	**560**	**-46.3**
21IGC [2]	--	**4**	--	-28	-21	-9	--	**280**	**-74.0**
BARC-JRQ [8]		**-1.4**	-76		-32			**524**	**-76.9**
BARC-JPG [8]		**-68.5**	-100		-75			**552**	**-112.8**
A1 [6]		**-32.6**	-74	-61		-39		434	**-93.6**
A2 [6]		**-44.9**	-86	-79		-56		465	**-100.2**
A3 [6]		**-51.6**	-89	-79		-61		479	**-103.7**
Steel5(AD)# [7]	-122*	**-103**	**-131.2**					414	**-131.2**
Steel5(SA)# [7]	-126*	**-32.6**	**-88.2**					579	**-93.6**
Steel7(AD)# [7]	-124*	**-50**	**-132.8**					726	**-102.9**
Steel7(SA)# [7]	-117*	**>20**	**-92**					896	**-62.8**

Note: Values indicated in bold face were derived from the respective literature data during the present investigation. All other values were taken directly from the literature.

*: *Drop-Weight NDT*; #: AD: As Delivered. SA: Strain Aged (10% CW + aging at 250 °C).

3. K_{Id} AND J_{Id} ESTIMATION: PROCEDURE/THEORY

3.1 Procedure 1: Modified Schindler Procedure (MSP)

This simply involves use of Eq. (1) given by Schindler [9,2] for computing J_{Id}:

$$J_0 = \frac{7.33 \cdot m \cdot C_V \cdot 10^{-3}}{1 - 1.47 \cdot (\frac{C_V}{s_{fd}})} \quad (1)$$

where C_V is the total CVN energy, i.e, the impact energy, J is in J·mm^{-2}, m is the power-law exponent (see [2] for further details as to how m is modified from that originally propsed by Schindler) and s_{fd} is the dynamic flow stress; J_{Id} is converted to K_{Id} using the usual relation. T_{0Sch}^{dy} is evaluated following the procedure in [2]. T_{0Sch}^{dy} can be used to estimate T_0 using the following empirical relation derived in [2]:

$$T_o = -76.18 + 0.534 T_{0Sch}^{dy} \quad (2)$$

3.2 Procedure I1: Fracture Stress to Yield Stress Ratio Procedure (FYRP)

In this procedure, the basic assumption is that microcleavage stress, s_f, is an intrinsic material property related to cleavage fracture and, hence, a proper material parameter for use with static/dynamic yield stress for predicting T_0 and, hence, MC. Basically, the new correlation is based on the assumption that s_f is independent of temperature and strain rate and hence the same for both static and dynamic tests. There is evidence in the literature showing both support [10] and contradiction [11] to this view. However, here it is assumed that s_f is a constant within experimental error. This will be so in most cases where MC is applicable and local cleavage fracture is governed by a criterion involving the operation of a critical stress (or strain modified stress) over a critical distance; in cases where local embrittlement like strain aging/grain boundary embrittlement operates then an invariant cleavage stress may not work and in such situations MC itself may not be applicable.

Table 2. Basic material properties used for establishing the FYRP (Procedure-II)

Steel	a	b	s_{ys}(RT)/MPa	s_f/MPa	s_f/s_{ys}(RT)	T_0/°C
21Holz	**1.4285**	**1.7093**	308.0	1700.0	**5.5195**	**-56.7**
SteelA	**0.1157**	**2.3882**	469.0	**2089.0**	**4.4542**	**-67**
SteelB	**0.1397**	**2.5419**	462.0	**2089.0**	**4.5216**	**-97**
JRQ	**0.0102**	**3.6311**	488.0	**1873.0**	**3.8381**	**-66**

Note: Values indicated in bold face were derived from the respective literature data during the present investigation. All other values were taken directly from the literature.

Basic properties of the four steels used for developing the new correlation are shown in Table 2. Based on the above considerations, the variation of the ratio, s_f/s_{yd}, with temperature has been related to the relevant static MC fracture toughness data; i. e., for the same temperature range, at various temperatures, the ratio, s_f/s_{yd}, was evaluated along with the corresponding static MC K_{IC}. Then the resulting, s_f/s_{yd}, values are plotted against the corresponding static MC K_{IC} and a smooth curve of the following form fitted:

$$K_{IC} = 20 + a.\exp(b\frac{s_f}{s_{yd}}) \quad (3)$$

where *a* and *b* are constants. Based on such fits, the constants *a* and *b* and the ratio, s_f/s_{ys}(RT) obtained for Steels A, B, JRQ and 21Holz are shown in Table 2. The constants *a* and *b* show an encouragingly predictable dependence on s_f/s_{ys}(RT). Now Fig. 1 shows the variation of *a* with s_f/s_{ys}(RT); similar smooth variation with s_f/s_{ys}(RT) is shown by constant *b* also. Smooth fits to the plots of *a* vs. s_f/s_{ys}(RT) and *b* with s_f/s_{ys}(RT) yield the following equations to predict *a* and *b*.

$$a = -0.0277 + (9.0848*10^{-6})*\exp(2.1713*\frac{s_{f}}{s_{ys}(RT)}) \qquad (4)$$

$$b = 21.1977 - 6.9727*\frac{s_{f}}{s_{ys}(RT)} + 0.6237*(\frac{s_{f}}{s_{ys}(RT)})^{2} \qquad (5)$$

Table 3 Application of FYRP (Procedure-II) to four steels

Material	T_0^{dy}, °C	PROCEDURE-II	
		s_f(MPa) & Fit Constants	T_{0PRS}^{st}/°C
91IGCBM	-52	s_f = 2425; *a* = 0.313; *b* = 2.051	-88.2
403SS-IGC		s_f = 2143; *a* = 0.001; *b* = 4.2491	-19.4
91WldIGC		s_f = 2140; *a* = 0.00876; *b* = 3.6601	-25
21IGC		s_f = 1561; *a* = 1.615; *b* = 1.71	-60.6

Now the application of the procedure simply consists in calculating s_f, s_{yd} vs. temperature, calculating the corresponding s_f/s_{yd} (well-established procedures in the field of instrumented CVN impact testing) and s_f/s_{ys}(RT). The latter when applied in Eqs. (4) and (5) yields the respective constants a and b which when put in Eq. (3) gives the MC K_{IC} values for each of the s_f/s_{yd} values estimated at various temperatures. Then the T-K_{IC} pairs (no size correction required as Eq. (3) predicts MC K_{IC}) between 80/85 to 115/120 MP√m are selected and analysed for the reference temperature (T_{0PRS}^{st}: the T_0^{st} obtained by FYRP) using the multi-temperature equation as given in [2].

4. RESULTS AND DISCUSSION

Figure 2 shows the T_0 determined experimentally plotted against T_0 predicted using Eq. (2) (i.e. MSP: open symbols). The 1:1 line and ± 15 °C lines are also shown. Excepting for Steels 7 and A1 (see Table 1), predictions by MSP (Procedure-I) are satisfactory for all other steels. Steel7 is a high strength steel and for it the YS-temperature relations applied to low to medium strength steels may not be appropriate. A1 may be an outlier. T_{0PRS}^{st} estimates for four steels (see Table 3) have also been plotted against predictions from Eq. (2) in Fig. 4 (closed symbols). The point for 91WldIGC falls just below the –15 °C line. However, T_0 predictions from FYRP are conservative (i. e., higher) as compared to those from Eq. (2). It may be noted that predictions from FYRP are very sensitive to accuracy of yield and fracture stress values. However, FYRP is based on fundamental material properties and hence has greater potential for accurate T_0 predictions. Both procedures need to be validated/tested/modified based on more accurate and complete data base spanning a range of materials from low to high strength levels and alloy compositions and full instrumented test data. The present relations seem to provide reasonably accurate T_0 predictions within 15 °C for steels with YS upto 600-650 MPa; for higher strength steels modified correlations may give better predictive accuracy. However, the present trends are encouraging for both Procedures (MSP & FYRP).

5. CONCLUDING REMARKS

- A correlation of reference temperature, T_0 with T_{0Sch}^{dy} proposed by the authors earlier has been applied to some new results from the literature and the results are encouraging.
- A new correlation has been obtained that relates the microcleavage fracture stress, s_f, to the static Master Curve (MC) and T_0 based on a knowledge of variation of dynamic yield stress, s_{yd}, with temperature, both of which are obtainable from instrumented CVN impact tests. This new methodology has been applied to four steels and the prediction of T_0 and MC are satisfactory when compared to other correlations.
- Both the methods seem to be promising and need validation/confirmation/modification based on application to more extensive and complete data set (i. e., data on a range of steels with full instrumented and MC data).

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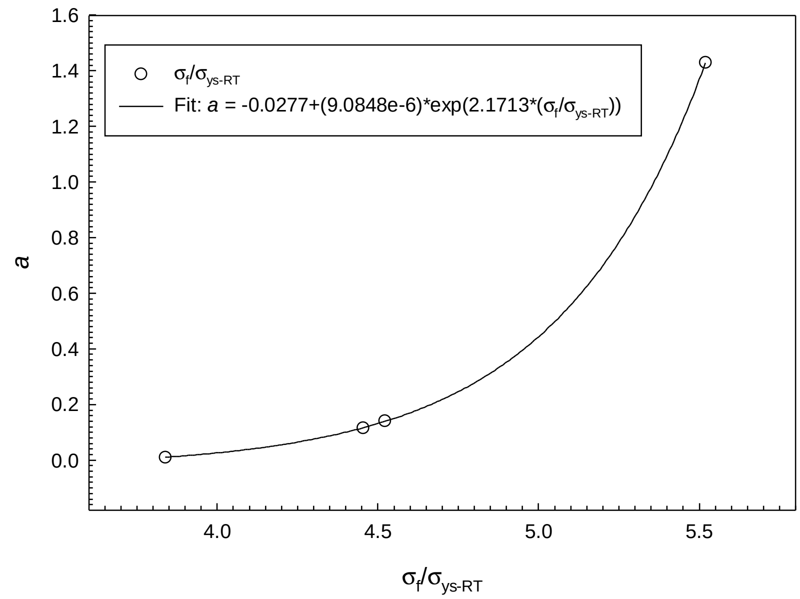

Fig. 1 Calibration graph giving the equation for constant *a*

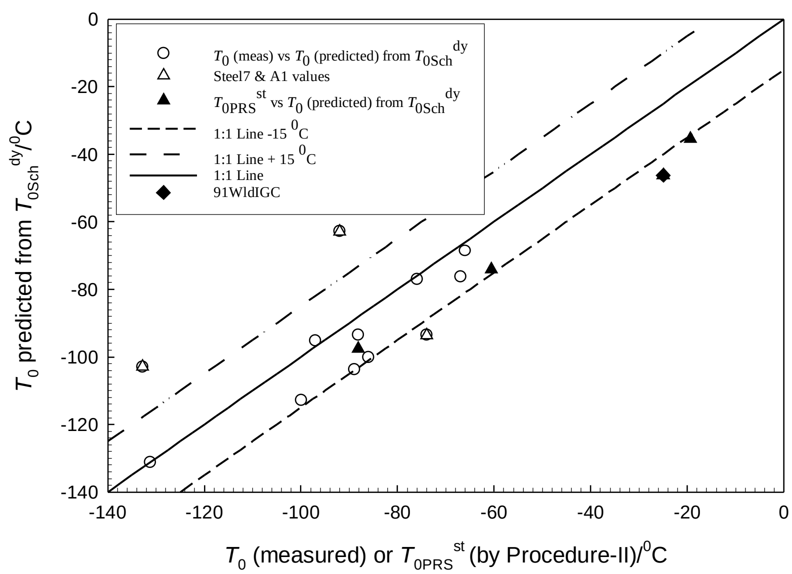

Fig. 2 Comparison of measured or estimated T_0 with T_0 predicted from T_{0Sch}^{dy}