ESTIMATION OF QUASI-STATIC *J-R* CURVES FROM CHARPY ENERGY AND ADAPTATION TO ASTM E 1921 REFERENCE TEMPERATURE ESTIMATION OF FERRITIC STEELS

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ABSTRACT

Many researchers had suggested a sort of scaling procedure for predicting the quasi-static *J-R* curves from dynamic *J-R* curves obtained from instrumented Charpy V-notch (CVN) impact tests using key-curve, compliance or other procedures. Chaouadi, based on extensive tests and literature data, had quantitatively formalized the method and suggested general applicability of his method for a class of steels. In this paper, first, Chaouadi-procedure is tried on some selected data from the literature (including the data used by Chaouadi and other workers) and an adaptation of the method is suggested using Wallin's as well as Landes's lower bound methods for upper-shelf *J-R* curve estimation from CVN energy. Using Chaouadi and other data as the benchmark, suitable scaling factors have been determined that enable estimation of quasi-static *J-R* curves from CVN energy alone, without the need for dynamic CVN *J-R* curves. The final formulae are given. This new method can be called modified Wallin-Landes procedure. Then this method is applied to fracture toughness and reference temperature (T_0 – ASTM E-1921) estimation from the full Charpy-transition data. The results are compared with those from the author's IGC-procedure, and modifications, if any, are suggested. Based on the new results, it is suggested that the IGC-procedure may be modified as: final $T_{Q-est} = T_{Q-IGC}$ for $T_{Q-Sch}^{dy} \leq 20$ °C (in the IGC-procedure the dividing temperature was 60 °C); and for $T_{Q-Sch}^{dy} > 20$ °C, $T_{Q-IGC} = T_{Q-WLm}$ (different from the IGC-procedure and subscript WLm indicating modified Wallin-Landes procedure). For the 59 or more steels examined (including highly irradiated steels), the T_{Q-WL} estimates at higher temperatures are consistent and conservative; a few non-conservative values are acceptably less than 20 °C, where as other predictions show non-conservatism of up to 40-50 °C. At lower temperatures, T_{Q-IGC} is consistently conservative and not over-conservative as the other estimates. The limitations suggested by Chaouadi for his method, namely, dependence on work-hardening, strain rate, yield stress, etc., hold good for the present method also and require further quantification based on finite element analysis, if necessary; however, these are not likely to affect the T_Q estimation significantly. K_{J-WLm} is better than RNB correlation in making a conservative or closer estimate of fracture toughness at the upper shelf.

INTRODUCTION

Charpy V-notch impact (CVN) test is very attractive because of its low-cost, simplicity and wide familiarity and availability compared to the more sophisticated and costly fracture mechanics test which requires very skilled manpower and special instrumentation [1,2]. For quantitative design involving assurance of structural integrity, fracture toughness data in terms of K_{IC} , J_{IC} or, its engineering equivalent, $J_{0.2}$, and fracture resistance *J-R* curves are required. To achieve this, many Charpy-fracture toughness correlations have been proposed; because of differences in loading rate, notch acuity, constraint etc. between the Charpy and fracture toughness tests, these lack universal applicability and are restricted to the specific material and test conditions for which they were derived [1-9]. However, some of the recent correlations are more promising from the point of view of producing design relevant fracture toughness properties that are consistently, and, often, assuredly, conservative [1,9]. This paper is an attempt to further extend these efforts. Aurich et al. [4] and Tronskar et al. [5] had suggested a sort of scaling procedure for predicting the quasi-static *J-R* curves from dynamic *J-R* curves obtained from instrumented CVN impact tests using key-curve, compliance or other procedures. They had given approximate scaling factors. Chaouadi [1,6], based on extensive tests and literature data, had quantitatively formalized the method and suggested general applicability of his method for a class of steels. Chaouadi [1] had suggested the need for quantifying the variation of the scaling factors depending on work-hardening index, yield stress, strain rate etc., based on finite element analysis also. In this paper, using Chaouadi and other data as the benchmark, an adaptation of the method is suggested using Wallin's [7] as well as Landes' [8] methods for upper-shelf *J-R* curve estimation from CVN energy. Methodology for obtaining the suitable scaling factors has been outlined that will enable estimation of quasi-static *J-R* curves from CVN energy alone, without the need for dynamic CVN *J-R* curves. The final formulae are given and the

results discussed. This new method can be called modified Wallin-Landes procedure. Then this method is applied to fracture toughness and reference temperature (T_0 – ASTM E-1921 [10]) estimation from the full Charpy-transition data. The results are compared with those from Sreenivasan's [9] IGC-procedure and modifications, if any, are suggested. Also, the effectiveness of the new formulae in predicting the upper-shelf fracture toughness is examined and compared with the results from the well known Rolfe-Novak-Barsom (RNB) equation [3].

BASIC METHODOLOGY AND MATERIALS

Basic Methodology

Fig. 1. Illustration of the Wallin and Landes procedure predictions and derivation of scaling factors

Aurich et al. [4] and Tronskar et al. [5] had suggested the possibility of obtaining quasi-static J - R curves from dynamic J - R curves obtained from instrumented impact tests of blunt-notched or precracked CVN specimens using appropriate scaling. The scaling factor was determined empirically, often with an additional factor involving the ratio of dynamic to static yield stress. Chaouadi and Puzzolante [1,6] had formalised these efforts in the following equations:

$$J_R^{\text{static}} = \alpha_{\text{LR}} \cdot \beta_{\text{config}} \cdot \left(\frac{\sigma_{\text{yd}}}{\sigma_{\text{ys}}} \right)^2 \cdot J_R^{\text{CVN impact}} \quad (1)$$

which for dynamic J_R reduces to:

$$J_R^{\text{dynamic}} = \beta_{\text{config}} \cdot J_R^{\text{CVN impact}} \quad (2)$$

where, $J_R^{\text{CVN impact}}$, represents the dynamic J_R -curve obtained from CVN impact test using key-curve, compliance or other procedures [1,6,11] and J_R^{dynamic} and J_R^{static} are the dynamic and quasi-static J_R -curves, respectively, obtained from deeply precracked specimens using standard fracture toughness tests; α_{LR} is a loading rate factor, β_{conf} is a factor accounting for notch acuity and configuration effects (V-notch vs. fatigue precrack), σ_{yd} and σ_{ys} are dynamic and static yield stress, respectively, at the test temperature. The square term arises from the consideration that J_R (J -resistance or crack resistance) is proportional to plastic zone size which is inversely proportional to the yield stress.

Chauoadi [1] has empirically determined $\alpha_{LR} = 0.46$; β_{conf} is given to be 0.52 at quasi-static loading rate and 0.84 at impact loading rate. J_R^{static} obtained from Eq. (1) using Chauoadi's factors ($\alpha_{LR} = 0.46$ and $\beta_{conf} = 0.52$) may be termed J_{Ch} . Figure 1 illustrates the application of Eq. (1) to the results for a C-Mn steel - E 460(3) – given in Aurich et al. [4].

Now, one disadvantage of the above procedure is that it requires instrumented impact test facility and sophisticated and careful data processing to obtain $J_R^{CVN\ impact}$, that is, the dynamic J_R -curve from CVN impact test. Recently, Wallin [7] as well as Gioielli, Landes et al. [8] have derived semi-empirical equations for estimating the static J_R -curve from the CVN energy, C_V (because of the unfamiliarity and difficulty of the name Gioielli, for convenience, the procedure or equation due to the latter is referred as Landes' equation in this paper; Prof. Landes is well known in the elastic-plastic fracture field). Wallin's [7] near-lower-bound correlation for predominantly ductile fracture (especially applicable to Charpy upper-shelf – US - region) is applicable in the temperature region -100 to 300 °C. In fact, this new correlation gives not only the initiation J -value, but also the J - Δa tearing resistance curve (J - R curve) as a function of C_V values in the US. The correlations are as given below:

$$J_W = J_{lmm} \Delta a^m \text{ [kJ.m}^{-2}, \text{ mm}] \quad (3)$$

where

$$J_{lmm} = 0.53 C_{V-US}^{1.28} \exp\left(-\frac{T-20}{400}\right) \text{ [kJ.m}^{-2}, \text{ J, } ^\circ\text{C}] \quad (3a)$$

and

$$m = 0.133 C_{V-US}^{0.256} \exp\left(-\frac{T-20}{2000}\right) - \frac{\sigma_{ys-RT}}{4664} + 0.03 \text{ [J, } ^\circ\text{C, MPa}] \quad (3b)$$

where σ_{ys-RT} is the yield stress at room temperature, C_{V-US} is the upper-shelf C_V value and T is the test temperature. The equation due to Landes [8] is as given below:

$$J_L = 139.75 \left(\frac{C_{V-US}}{3.15} \right) (\Delta a)^{0.5} \text{ [kJ.m}^{-2}, \text{ J, m}] \quad (4)$$

The J value from Eq. (3), that is due to Wallin, will be referred as J_W , and that from Eq. (4), that is due to Landes, will be referred as J_L . The J_W and J_L obtained for the steel in Fig. 1 are shown along with the quasi-static J_R -curve (QS- J_R or J_{R-QS}).

As Eqs. (3) and (4) already incorporate a sort of notch effect and strain rate factors, only a simple multiplicative scaling is considered sufficient (unlike in the case of Eqs. (1) and (2)). The scaling factors are obtained by taking the ratios of J_{R-QS}/J_W and J_{R-QS}/J_L ; the average ratios obtained for the results in Fig. 1 are 1.55 and 2.295, respectively (i.e., over the whole range of $\Delta a = 1.4$ -1.5 mm shown in Fig. 1). Similarly, ratios are found for various other steels. Other results and comparisons are given in detail later.

Materials

For calibration of the procedure, that is for determining the scaling factors as discussed in the previous paragraph, the data for the steels tested mainly at 20-25 °C or 280-300 °C and described in Aurich [4], Blauel [12], Eberle [13], Yoon [14] and El-Fadaly [15] have been used. For later comparison of the reference temperature estimates, apart from the above steels (only those for which full transition range Charpy data are available), all the steels described in Sreenivasan [9] have been used along with a few other steel data culled from recent literature, which are not listed here to restrict the bulk of the paper.

RESULTS AND DISCUSSION

Modified Wallin-Landes Procedure for J_R curve estimation

For calibration, the scaling factors, J_{R-QS}/J_W and J_{R-QS}/J_L , have been determined for the steels listed in Table 1. The average scaling factors are 1.656 and 2.146 for J_{R-QS}/J_W and J_{R-QS}/J_L , respectively, though for the particular steel shown in Fig. 1, they were 1.55 and 2.295, respectively. For the present purpose, for representing the material J_R -curve, a mean value of $(1.656J_W + 2.146J_L)/2$ is proposed to be taken, where J_W and J_L are obtained from Eqs. (3)

and (4) respectively. The J_R -curve based on the mean value is called the J based on modified Wallin-Landes procedure, represented by J_{WLm} (subscript indicating Wallin-Landes-modified). This is given as Eq. (5).

Fig. 2. Application of the modified Wallin-Landes procedure to an X-52 grade pipeline steel (Tyson et al. [16]) and a CrMoNi steel (Blumenauer et al. [17])

Table 1. Scaling factors determined for various steels (source references listed in square brackets)

Steel	J_{R-QS}/J_{R-W}	J_{R-QS}/J_{R-L}	Test Temp/ °C	C_V / J	YS/MPa
Eberle:St460 [13]	1.8420	2.5130	25	78	470
Aurich:E460(3) [4]	1.5500	2.2950	20	104	480
Blaue1 :20MnMoNi55[12]	1.3880	1.8790	80	161	464
Blaue1:20MnMoNi55 [12]	1.3947	1.5992	150	155	441
Blaue1:20MnMoNi55 [12]	2.1073	1.6550	300	145	433
20MnMoNi55:BM [15]	1.6460	2.8230	25	194	454
20MnMoNi55: -10%PD [15]	1.1390	1.9360	25	201	509
Yoon:Mod9Cr1Mo [14]	1.7640	2.8340	25	187	520
Yoon:Mod9Cr1Mo [14]	2.0732	1.7750	288	260	476
Computed values					
Mean	1.656	2.146			
SD	0.325	0.485			
Std. Error	0.108	0.162			
95% Confidence Level	0.250	0.373			
99% Confidence Level	0.363	0.543			

$$J_{WLm} = \frac{1.656J_W + 2.146J_L}{2} \quad (5)$$

In Fig. 1, the J_{WLm} curve shows fair agreement with the J_{R-QS} curve; in fact, it shows much better agreement with the J_{R-QS} curve than the curve obtained by the Chaouadi procedure, J_{Ch} (Eq. (1)). For all the steels for which Chaouadi [1,6] has demonstrated his method (i.e., Eq. (1)), the predictions from Eq. (5) are excellent when

compared with the respective quasi-static J_R curves (all the data used in the present calibration are different from those used by Chaouadi). Hence, this agreement is very satisfactory.

Fig. 3. Comparison of the J_{WLm} with J_{Ch} or J_{QS} ($QS-J_R$) for a 9Cr1Mo steel [18] and a modified 9Cr1Mo steel [14]

In fact, for some different steels, for which the Chaouadi method doesn't work, use of Eq. (5) results in excellent agreement with the QS data. Two such cases are shown in Fig. 2. For the X-52 steel the agreement extends to very large crack extension upto 6-7 mm while for the CrMoNi steel, the J_{WLm} curve is acceptably conservative at large crack extensions. The results for a 9Cr1Mo steel [18] and a modified 9Cr1Mo steel [14] are presented in Fig. 3. The dynamic J_R curve for the 9Cr1Mo steel shown in Fig. 3 was determined by Sreenivasan [18] from the instrumented impact test results of CVN (non-precracked) specimens by applying the key-curve procedure described in Sreenivasan et al. [11]; the agreement between the J_{Ch} and J_{WLm} curves is quite good. For the modified 9Cr1Mo steel (Yoon et al. [14]) shown in Fig. 3, the 25 °C results are acceptably (but not excessively) conservative (i. e., $J_{WLm} < J_{QS}$) while the 288 °C results are non-conservative, but within the scatter expected for J values - Sreenivasan et al. [19]. The relevant mechanical data for the steels shown in Figs. 2 and 3 are given in Table 2.

Table. 2. Relevant mechanical data for steels shown in Figs. 2 and 3 (source references listed in square brackets)

Steel	Test Temp/ °C	YS / MPa	Dy. YS / MPa	C_V / J	RT-YS / MPa	Remarks
X-52 (Tyson et al. [16])	23	376	554	65.5	376	IIT* + QS#
CrMoNi (Blumenauer et al. [17])	25	447	603	160	447	IIT+ QS
9Cr1Mo (Sreenivasan [18])	21	515	668	244	515	Only IIT
Mod. 9Cr1Mo (Yoon et al. [14])	25	525	670	187	525	No IIT
Mod. 9Cr1Mo (Yoon et al. [14])	288	476	473	260	525	No IIT

*: IIT - Instrumented Impact Test; #: QS – Quasi Static

Application of K_{J-WLm} for Estimation of ASTM E 1921 Reference Temperature (T_0)

Modified Wallin-Landes procedure for J_R curve estimation was described in the previous section. One thing that emerges from the previous section is that though J_R curve by the Wallin-Landes procedure may differ from the actual $QS-J_R$ curve (conservatively, and, sometimes, non-conservatively), the commonly used engineering estimate of J , $J_{0.2}$, may be close to the actual values. This is obtained by taking $\Delta a = 0.2$ mm in Eqs. (3)-(5); the

Fig. 4. Residuals various reference temperature estimates compared with that of T_{Q-WL}

corresponding K_{J-WLm} can be estimated by the usual conversion formula ($K_J = \sqrt{EJ/(1 - \nu^2)}$). Though Eqs. (3)-(5) have been restricted to be applicable to the fully ductile upper shelf, for our purpose we remove that restriction and apply the Eqs. (3)-(5) over the whole range of Charpy transition to obtain the corresponding K_J , taking $\Delta a = 0.2$ mm. Then the K_{J-WLm} values corresponding to the straight line portion of the CVN transition curve are taken to estimate an equivalent of T_0 . This can be done by superimposing an eye-fit straight on the linear portion of the Charpy transition curve avoiding the lower shelf. Then starting from the lowest value on the straight line portion a range of values up to 50-70 MPa $\sqrt{m}$ above the lowest value are taken with the corresponding temperatures and these are applied to the multi-temperature Wallin formula (Eq. (6)) to yield an estimate of T_0 , namely, T_{Q-WL} . Since all the calibrations given Table 1 pertain to 1" thick quasi-static test, the K_{J-WLm} values obtained from J_{WL} are considered as pertaining to 1" specimen tests. Equation (6) is as given below [10,9]:

$$0 = \sum_{i=1}^{i=n} \frac{\delta_i \exp\{0.019(T_i - T_0)\}}{[31 - K_{\min} + 77 \exp\{0.019(T_i - T_0)\}]} - \sum_{i=1}^n \frac{(K_{J-WL} - K_{\min})^4 \exp\{0.019(T_i - T_0)\}}{[31 - K_{\min} + 77 \exp\{0.019(T_i - T_0)\}]^5} \quad (6)$$

where the Kronecker $\delta_i = 1$, $K_{\min} = 20$ MPa $\sqrt{m}$, T_i is the test temperature and $T_0 = T_{Q-WL}$. The validity conditions and other requirements as required by ASTM E 1921 [10] are not examined. The K_{J-WLm} values for application in Eq. (6) range from 100-170 to 200-270 MPa $\sqrt{m}$, depending on the steel.

Figure 4 shows the residuals of the T_{Q-WL} values (i. e., T_0 (test) - T_{Q-WL}) for about 59 steels (all steels mentioned in [9] plus some additional steels) in comparison with other estimates discussed in [9] (T_{Q-IGC} : T_{Q-est} based on the IGC procedure described by Sreenivasan [9] and T_{Q-41J} : taking $T_{Q-est} = T_{41J}$, the 41J Charpy transition temperature, a very conservative estimate). It can be seen that T_{Q-WL} is either as much conservative or more over the whole range of T_0 values ranging from about -140 to +140 °C examined in Fig. 4. The steels in Fig. 4 are arranged with increasing T_{Q-Sch}^{dy} (a dynamic fracture toughness based reference temperature estimate as described in [9] which is necessary to estimate T_{Q-IGC}) from left to right ranging from -100 to 230 °C. In fact, for the high temperature steels to the right of the vertical line shown in Fig. 4 (i. e., $T_{Q-Sch}^{dy} > \sim 20$ °C), T_{Q-WL} shows more consistency in producing assuredly conservative values than T_{Q-IGC} . So the criterion given in [9] may be modified as: $T_{Q-est} = T_{Q-IGC}$ for $T_{Q-Sch}^{dy} \leq 20$ °C and $T_{Q-est} = T_{Q-WL}$ for $T_{Q-Sch}^{dy} > 20$ °C. The limitations suggested by Chaouadi for

his method, namely, dependence on work-hardening, strain rate, yield stress, etc., hold good for the present method also and require further quantification based on finite element analysis, if necessary; however, these are not likely to affect the T_Q estimation significantly.

Fig. 5. Comparison of K_{J-WLm} (for $\Delta a = 0.2$ mm) at the upper shelf with the predictions from RNB correlation for 27 steels

K_{J-WLm} as an Upper Shelf Fracture Toughness Estimator

As described in the previous section, estimates of J_{WLm} values at the upper shelf corresponding to $\Delta a = 0.2$ mm will give the upper shelf K_{J-WLm} using the usual conversion formula. The results for 27 steels are shown in Fig. 5 in comparison with predictions from the RNB correlation [3]. The conservatism of the K_{J-WLm} for all the steels is obvious - closer to or below the 1:1 line. In fact, the filled symbols shown in Fig. 5 pertain to the 11 steels that went into the original RNB correlation. K_{J-WLm} is better than RNB correlation in making a conservative or closer estimate of fracture toughness at the upper shelf.

CONCLUSION

Chaouadi procedure predicts the quasi-static $J-R$ curves from dynamic $J-R$ curves obtained from instrumented Charpy V-notch (CVN) impact tests. Wallin and Landes formulae predict lower bound upper shelf fracture toughness and quasi-static $J-R$ curves from CVN energy. Using Chaouadi and other data as the benchmark, suitable scaling factors have been determined that enable estimation of quasi-static $J-R$ curves from CVN energy alone by application of the Wallin and Landes formulae, without the need for dynamic CVN $J-R$ curves. The final formulae are given. This new method can be called modified Wallin-Landes procedure. Then this method is applied to fracture toughness and reference temperature (T_0 – ASTM E-1921) estimation from the full Charpy-transition data. The results are compared with those from the author's IGC-procedure, and modifications, if any, are suggested. Based on the new results, it is suggested that the IGC-procedure may be modified as: final $T_{Q-est} = T_{Q-IGC}$ for $T_{Q-Sch}^{dy} \leq 20$ °C (in the IGC-procedure the dividing temperature was 60 °C); and for $T_{Q-Sch}^{dy} > 20$ °C, $T_{Q-IGC} = T_{Q-WLm}$ (different from the IGC-procedure and subscript WLm indicating modified Wallin-Landes procedure). For the 59 or more steels examined (including highly irradiated steels), the T_{Q-WL} estimates at higher temperatures are consistent and conservative; a few non-conservative values are acceptably less than 20 °C, where as other predictions show non-conservatism of up to 40-50 °C. At lower temperatures, T_{Q-IGC} is consistently conservative and not over-conservative as the other estimates. The limitations suggested by Chaouadi for his method, namely, dependence on work-hardening, strain rate, yield stress, etc., hold good for the present method also and require

further quantification based on finite element analysis, if necessary; however, these are not likely to affect the T_Q estimation significantly. K_{J-WLm} is better than RNB correlation in making a conservative or closer estimate of fracture toughness at the upper shelf.

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