International Journal of Pressure Vessels and Piping 134 (2015) 101–111

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

# Standard and customized correlation of crack resistance curves and Charpy upper shelf energy for German reactor pressure vessel steels

Jörg Hohe [a,*], Dieter Siegele [a], Eduard Bechler [b], Gerhard Nagel [c]

[a] Fraunhofer Institut für Werkstoffmechanik, Wöhlerstr. 11, 79108 Freiburg, Germany
[b] E.ON Nuclear Power, Tresckowstraße 5, 30457 Hannover, Germany
[c] KompInt GmbH, Hindenburgdamm 96, 12203 Berlin, Germany

ARTICLE INFO

*Article history:*
Received 13 January 2014
Received in revised form
7 August 2015
Accepted 28 August 2015
Available online 1 September 2015

*Keywords:*
Crack resistance curve
Charpy upper shelf energy
Correlation
Engineering approach

ABSTRACT

In order to avoid extensive and expensive testing of the $J_R$ crack resistance behavior of reactor pressure vessel steels, different correlations between the upper shelf energy obtained from Charpy impact tests and the crack resistance curve have been proposed in the literature. To analyze their applicability and the amount of conservatism, the most important correlation formulas have been compared with measured $J_R$-curves for different German reactor pressure vessel steels. For these materials, an alternative customized correlation is proposed. All correlations investigated are found to provide reliable and conservative estimates of the crack resistance curves for temperatures up to 300 °C.

## 1. Introduction

Standard integrity assessments of structural components at higher temperatures in the ductile failure range in engineering application are usually based on the $J_R$ crack resistance curve, providing a unique relation between the $J$-Integral as a loading parameter and the corresponding ductile crack extension $\Delta a$. By means of this concept, the ductile crack advance to be expected for any postulated flaw under any loading condition can easily be determined by comparison of the computed applied crack front load $J$ for the considered component and flaw geometry with the material specific crack resistance curve $J_R(\Delta a)$.

The experimental determination of $J_R$ crack resistance curves is in general performed according to ASTM standard E 1820 [1]. The determination of crack resistance curves is expensive due to the large amount of material required for the multiple specimen option on one hand or the time consuming procedure and the more sophisticated experimental setup required for the single specimen option with determination of the crack depth from the specimen compliance during partial unloading cycles or from electrical potential measurements. Furthermore, the necessary amount of material to comply with the specimen size requirements defined in ASTM E 1820 [1] might in many cases not be available, especially for the irradiated state.

In order to avoid these difficulties and expenses, different approaches to estimate the crack resistance curve from the results of Charpy impact tests have been proposed in the literature. Since Charpy specimens tested in the upper shelf fail in a ductile mode, an interrelation between the level of the upper shelf energy (USE) describing the failure resistance of the Charpy specimens in this range and the crack resistance curve describing the ductile failure of the fracture mechanics specimen has to be expected. The oldest correlation among the most common approaches has been provided by Merkle and Johnson [3,4], who interrelated the parameters of the power law fit of the experimentally determined crack resistance curve according to ASTM E 1820 [1] with the upper shelf energy determined in Charpy impact test on the same material. In order provide an improved approximation of the initial part of the crack resistance curve, an enhanced analytical approximation of the experimentally determined crack resistance curve has been proposed by Reg. Guide 1.161 [2]. Again, the corresponding parameters are interrelated with the Charpy upper shelf energy. In addition, this approach accounts explicitly for temperature effects, allowing a reduction of conservatism. In a recent study, Wallin [6,7], proposed again a power law type form of a upper shelf energy dependent crack resistance curve. Based on the evaluation of 112 experimental data sets, this study provides an explicit and more accurate description of the temperature dependence compared to previous approaches.

---

[*] Corresponding author.
*E-mail address:* joerg.hohe@iwm.fraunhofer.de (J. Hohe).

http://dx.doi.org/10.1016/j.ijpvp.2015.08.009

In the present study, the aforementioned correlations between the crack resistance curves and the Charpy upper shelf energy are validated in a comparative study on an experimental data base consisting of different German reactor pressure vessel steels, extending a previous contribution by the authors (Siegele et al. [5]). The materials were tested in the range from 100 °C to 290 °C. Both, base metals and welds are included. Subsequently, a customized correlation for the materials in the experimental data base based on Wallin's approach [6] [7], is proposed. The customized correlation provides reliable and conservative estimates on the respective $J_R$ curves of the materials investigated.

## 2. Experimental data base

As an experimental reference for the present study, a data base consisting of crack resistance curves for German reactor pressure vessel steels is available, consisting of seven different base metals and four welds (22NiMoCr37 and 20MnMoNi55). For these materials, crack resistance curves according to ASTM E 1820 [1] were determined on C(T) 25 specimens using the single specimen technique with partial unloading for determination of the actual crack length from the specimen compliance. The tests were performed between 80 °C and 100 °C, at 200 °C and at service temperature between 270 °C and 288 °C, depending on the individual material. The Charpy upper shelf energy as well as the yield strength $R_{p0.2}$ and the ultimate strength $R_m$ were available from the basic characterization of the respective material heat.

The experimental crack resistance results for the different base metals A to G and the welds H to M are compiled in Fig. 1. In this figure, as well as in all subsequent figures, valid $J_R$ data according to ASTM 1820 [1] with

$$J \leq J_{\max} \tag{1}$$

and

$$\Delta a \leq \Delta a_{\max} \tag{2}$$

are marked by filled symbols whereas additional data points beyond these limits are added for information, marked by open symbols. The limits according to Equations (1) and (2) together with the average yield strength $\sigma_y = (R_{p0.2} + R_m)/2$ and the parameters $C_1$ and $C_2$ of the power law fit

$$J_R(\Delta a_{\max}) = C_1 \Delta a^{C_2} \tag{3}$$

of the crack resistance curve according to ASTM 1820 [1] are compiled in Table 1. In addition, the individual test temperatures $T$ and the Charpy upper shelf energies $USE$ are presented.

As expected, the levels and slopes of the crack resistance curves decrease with increasing test temperature. Strong effects are observed especially in the lower temperature range from $T = 100$ °C–200 °C whereas only weak effects are present in the upper temperature range between $T = 200$ °C and service temperature at 280 °C. A distinct scatter of the $\Delta a$ data of the individual crack resistance curves, especially in the initial stage of the experimentally determined $J_R$ curves is caused by uncertainties in the crack length measurement using the specimen compliance method. Nevertheless, since the crack length measurements from the compliance method during the crack resistance experiment is validated by an optical measurement on the crack surface after completion of the crack extension experiment, it is ensured that the crack extension measurement provides the correct average crack extension.

A comparison of the individual crack resistance curves shows that two materials, base metal B and weld M, possess significantly lower crack resistances compared to the other materials in the respective material group (base metals or welds). On the other hand, these two materials also possess the lowest Charpy upper shelf energy $USE$ (see Table 1), giving a first evidence of the possibility to correlate the $J_R$ crack resistance curves with the upper shelf energy. Furthermore, the – in general – slightly lower crack resistance curves for the welds correlate with a slightly lower average upper shelf energy (base metals: 182 J, welds: 175 J).

## 3. Correlations between $J_R$ curves and Charpy upper shelf energy

### 3.1. Available correlations

#### 3.1.1. NUREG-0744

Several approaches for correlation between the $J_R$ crack resistance curves and Charpy upper shelf energy $USE$ have been proposed in the literature. One of the earlier approaches has been proposed by Merkle and Johnson [3,4], (NUREG-0744). In this correlation, the parameters $C_1$ and $C_2$ in the power law fit (3) of the crack resistance curve according to ASTM E 1820 [1] are interrelated with the Charpy upper shelf energy by

$$C_1 = -114\frac{USE}{100} + 5382\left(\frac{USE}{100}\right)^2 \tag{4}$$

$$C_2 = \frac{0.473x^3}{14.42 + x^3} \tag{5}$$

$$x = \frac{C_1}{1000} + 0.015\sigma_y \tag{6}$$

where $\Delta a$, $USE$ and $\sigma_y$ have the units of inch, lbf ft and ksi respectively, whereas $J_R(\Delta a)$ is obtained in lbf/inch. The temperature dependence of the crack resistance curves is not included explicitly into Equations (4)–(6) but is accounted in an implicit manner through the temperature dependence of the average yield stress $\sigma_y$ in Equation (6).

#### 3.1.2. Reg. Guide 1.161

An alternative correlation between the crack resistance curve and the Charpy upper shelf energy has been proposed in Reg. Guide 1.161 [2]. In this approach, an alternative mathematical approximation

$$J_R(\Delta a) = C_1 \Delta a^{C_2} \exp\left(C_3 \Delta a^{C_4}\right) \tag{7}$$

of the crack resistance curve is proposed, where the original power law (3) is enhanced by an exponential function which – by means of an appropriate choice of the additional parameters $C_3$ and $C_4$ – decays with increasing crack propagation $\Delta a$. In general, this enhancement of the original power law provides a better approximation of the initial part of the crack resistance curve, which in some cases is overestimated by the power law form (3), if the fit of the experimental data is performed for a wider range of crack propagations $\Delta a$ than proposed in ASTM E 1820 [1]. The parameters $C_1$ to $C_4$ in Equation (7) are interrelated with the upper shelf energy by

$$MF = \begin{cases} 0.749 & (levels\ A,\ B,\ C) \\ 1 & (level\ D) \end{cases} \tag{8}$$