THE VTT METHOD FOR ASSESSMENT OF FRACTURE RESISTANCE FOR STRUCTURAL STEELS FROM SMALL MATERIAL SAMPLES

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Often, like for operational structures, it is impossible or inappropriate to obtain large material samples for standard fracture toughness determination. This is especially the case with irradiation damage assessment of reactor pressure vessels, but also many other applications have the same restrictions. The VTT method is a holistic approach by which to determine static, dynamic and crack arrest fracture toughness properties either directly or by correlations from small material samples. As a result of the method, statistically defined fracture toughness estimates, of the material, suitable for structural integrity assesment are obtained.

INTRODUCTION

Present fracture toughness testing standards require the use of comparatively large test specimens to obtain so called valid fracture resistance values. Extreme standards in this respect are the linear-elastic K_{IC} standard and the CTOD standard that require full section thickness specimens. Often, like for operational structures, it is impossible or inappropriate to obtain large material samples for standard fracture toughness determination. This is especially the case with irradiation damage assessment of reactor pressure vessels, but also many other applications have the same restrictions.

At VTT, development work has been in progress for 15 years to develop and validate testing and analysis methods applicable for fracture resistance determination from small material samples. The VTT method is a holistic approach by which to determine static, dynamic and crack arrest fracture toughness properties either directly or by correlations from small material samples (Fig. 1).

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As a result of the method, statistically defined fracture toughness estimates, of the material, suitable for structural integrity assesment are obtained. Here, the VTT method is highlighted through two examples describing the determination of brittle fracture resistance and crack arrest.

FRACTURE RESISTANCE

The method for fracture resistance estimation is based on a statistical brittle fracture model, which gives for the scatter of fracture toughness (Wallin (1)),

$$P\left[K_{IC} \le K_I\right] = 1 - \exp\left(-\left[\frac{K_I - K_{min}}{K_0 - K_{min}}\right]^4\right) \tag{1}$$

where $P[K_{IC} \le K_I]$ is the cumulative failure probability, K_I is the stress intensity factor, K_{min} is the theoretical lower bound of fracture toughness and K_0 is a temperature and specimen size dependent normalization fracture toughness, that corresponds to a 63.2 % cumulative failure probability being approximately 1.1 $\cdot \overline{K}_{IC}$ (mean fracture toughness). The model include a statistical size correction of the form (Wallin (2)),

$$K_{B_2} = K_{min} + [K_{B_1} - K_{min}] \cdot \left(\frac{B1}{B2}\right)^{1/4} \tag{2}$$

where B_1 and B_2 correspond to respective specimen thickness (length of crack front).

Close to the lower shelf of fracture toughness (K_{IC}<<50 MPa√m) the equations are expected to be inaccurate. The model is based upon the assumption that brittle fracture is primarily initiation controlled, even though it contains a conditional crack propagation criterion, which among others is the cause of the lower bound fracture toughness K_{min}. On the lower shelf, the initiation criterion is no longer dominant, but the fracture is completely propagation controlled (Wallin (3)). In this case there is no statistical size effect (eq 2) and also the toughness distribution differs (not very much) from eq 1. In the transition region, which is of main interest for the present work, however, eqs 1 and 2 should be valid as long as loss of constraint and/or ductile tearing do not play a significant role (Wallin (4)).

For structural steels, a "master curve" describing the temperature dependence of fracture toughness has been proposed (Wallin (5)),

$$K_0 = 31 + 77 \cdot \exp(0.019 \cdot [T - T_0]) \tag{3}$$

where T_0 is the transition temperature where the mean fracture toughness, corresponding to a 25 mm thick specimen, is 100 MPa√m and K_0 is 108 MPa√m.

Eq 3 gives an approximate temperature dependence of the fracture toughness for ferritic structural steels and it is comparatively well verified. Keeping the temperature dependence fixed, decreases the effect of possible invalid fracture toughness values upon the transition temperature T_0.

The maximum likelihood estimate, for a randomly censored data set, for estimating T_0 when the scatter obeys eq 1 and $K_0 = a + b \cdot \exp\{c \cdot [T - T_0]\}$, with the parameters a, b and c being fixed becomes,

$$\sum_{i=1}^{n} \frac{\delta_i \cdot \exp\{c[T_i - T_0]\}}{a - K_{min} + b \cdot \exp\{c[T_i - T_0]\}} - \sum_{i=1}^{n} \frac{(K_{IC_i} - K_{min})^4 \cdot \exp\{c[T_i - T_0]\}}{(a - K_{min} + b \cdot \exp\{c[T_i - T_0]\})^5} = 0 \qquad (4)$$

from where T_0 can be solved iteratively. Kroneckers delta (δ_i) is one (1) when K_{IC} corresponds to failure by brittle fracture and $\delta_i = 0$ when K_{IC} corresponds to non-failure (end of test value).

An example of the efficiency of the VTT method is presented in figs. 2 and 3. Fig. 2 containes raw data for the 73W weld and fig. 3 contain the data as analysed by the VTT method.

CRACK ARREST

Typically, in an instrumented impact test load trace corresponding to the ductile/brittle transition region cleavage fracture initiates at the load F_u. However, often the specimen does not fracture completely, but the crack arrests at load F_a. The load F_a shows an increasing temperature dependence. At low temperatures the cleavage crack will propagate completely through the specimen, whereas at higher temperatures the crack will arrest at increasingly higher load values. Thus F_a is connected to the materials crack arrest toughness K_{Ia}. It is possible to define a transition temperature based on the fracture arrest parameter F_a. In the VTT method, the mean temperature corresponding to a fixed arrest load, equal to 4 kN, ($T_{Fa=4kN}$) has been selected as transition criteria (Wallin (6)).

The temperature dependence of the K_{Ia} data is described by the equation

$$K_{Ia} = 30 + 70 \cdot \exp\{0.019 \cdot (T - TK_{Ia})\} \qquad (5)$$

where TK_{Ia} corresponds to the temperature where the mean K_{Ia} is equal to 100 MPa√m. Eq 5 is of the same form as the equation determined earlier for the description of the brittle fracture initiation toughness.

The scatter in K_{Ia} is assumed to be lognormal so that the proportional scatter in K_{Ia} is constant. An example of the analysis is presented in fig. 4. The assumed temperature dependence and distribution is seen to describe the data quite well. Thus it is possible to normalize the K_{Ia} transition curve, based only on TK_{Ia}. Additionally, the same temperature dependence that is also used to describe the brittle fracture initiation toughness can be used. The scatter in K_{Ia} appears less than for K_{Jc}.

The correlation including all examined materials is presented in fig. 5. With the exception of PTSE-2 all materials yield a very clear correlation between T_{Fa4kN} (as measured by the Charpy-V specimen) and TK_{Ia}. The PTSE-2 material differs from the other materials by having a low yield strength combined with a low upper shelf toughness. These differences may explain the found behavior. The standard deviation of the correlation is only $\sigma = 12.4$ °C.

It is clear that the Charpy-V fracture arrest parameter T_{Fa4kN} has a comparatively good descriptive potential with respect to crack arrest K_{Ia}

ACKNOWLEDGEMENTS

This work is a part of the Material Degradation in Reactor Environment project (RAVA) belonging to the Structural Integrity of NPP:s research programme (RATU2), performed at VTT Manufacturing Technology and financed by the Ministry of Trade and Industry in Finland, VTT, the Finnish Centre for Radiation and Nuclear Safety and Finnish Nuclear Power industy.

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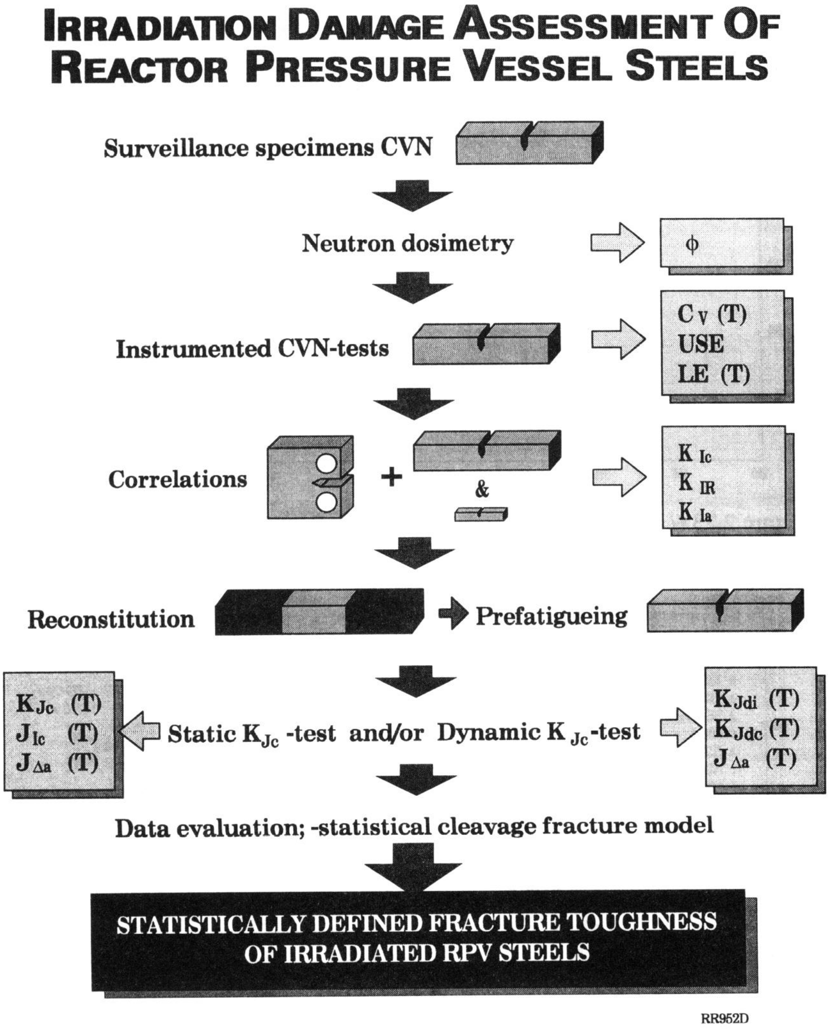

Figure 1 The VTT method for assessment of fracture resistance

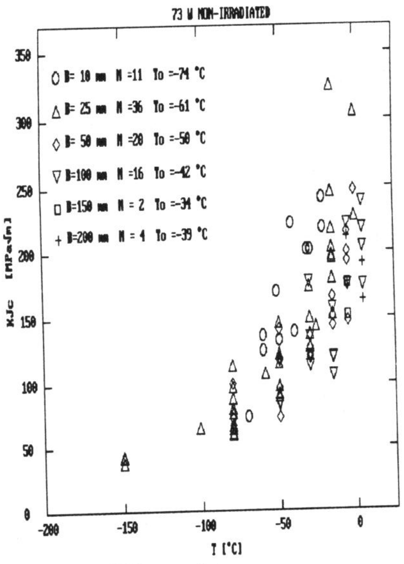

Figure 2 73W raw data

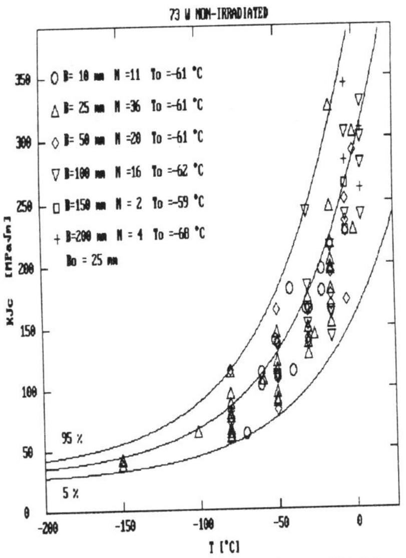

Figure 3 73W analysed with the VTT method

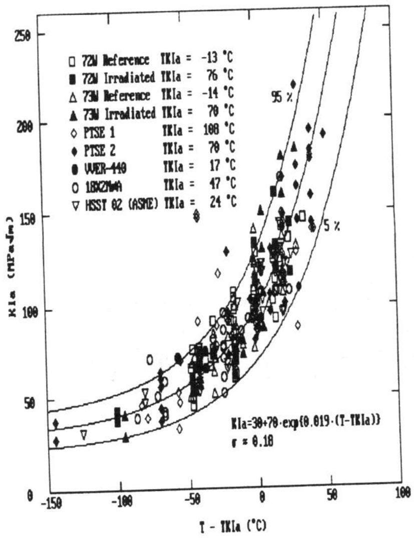

Figure 4 K_{Ia} master curve

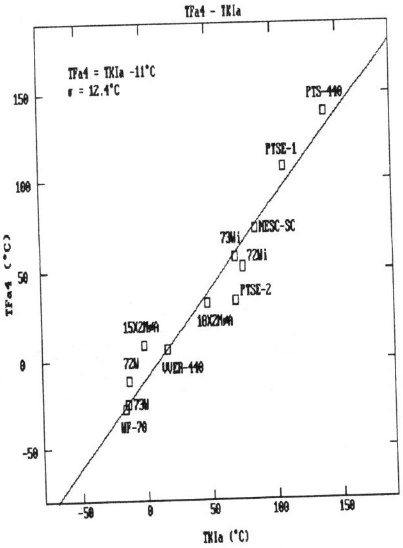

Figure 5 K_{Ia}-TF_{a4kN} correlation