Theory Based Statistical Interpretation of Fracture Toughness of Reactor Pressure Vessel Steel 15x2MΦA and its Welds

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INTRODUCTION

A large number of fracture toughness results exist for the nuclear pressure vessel steel 15X2MΦA, which is used in Soviet type 440 MW pressurized water reactor pressure vessels. The available data has earlier been analyzed by normal statistical means in order to create lower bound reference curves for fracture toughness. Recent developments in the theoretical modelling of cleavage fracture initiation have led to a statistical description of the macroscopic fracture toughness. It has thus become possible to make a theoretical interpretation of the scatter in fracture toughness of the reactor pressure vessel steel 15X2MΦA.

This work focusses on recent fracture toughness results obtained for five different heats of base material and two different types of welds at different temperatures. All plates are of standard composition and have had a normal heat treatment. The fracture toughness results are analyzed by the so called WST model, which for a "sharp" crack yields a simple distribution function describing both the statistical specimen size effect as well as the theoretical scatter of the fracture toughness values. The results for the different materials are all size corrected to correspond to a specimen thickness of 25 mm and the experimental scatter is compared to the expected theoretical scatter. Additionally a theoretical Charpy-V - K_{IC} correlation is validated for the PWR-440 MW materials. Finally, theoretical statistical reference curves for the steels are presented and compared to the presently used standard reference curves.

EXPERIMENTAL

The materials used in the investigation consisted of five different heats of the 15X2MΦA base material and two different corresponding welds, two submerged arc welds (SAW) and one electroslag weld (ESW). The mechanical properties at room temperature for the materials are presented in Table 1. In all cases the section size of the materials was 150 mm.

Table 1. Room temperature mechanical properties of test materials.

Material	Heat	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	A_5 (%)	Z (%)
15X2MΦA	108348	601	701	20.5	74.2
15X2MΦA	103219	576	686	21.2	73.0
15X2MΦA	103405	602	702	20.2	73.1
15X2MΦA	109545	530	658	22.6	74.3
15X2MΦA	101302	512	717	22.1	72.5
Cb10XMFT	SAW (12)	400	551	-	-
Cb10XMFT	SAW (22)	479	602	21.5	72.1
Cb13X2MFT	ESW	539	626	19.7	74.9

The mechanical testing was performed within a cooperative program between VTT (Technical Research Centre of Finland) and various research institutes in the Soviet Union. The fracture toughness tests were partly performed by VTT and partly by the Soviet institutes. The specimen geometries were both 3PB and CT with thicknesses ranging from 25 mm to 150 mm. Two different analysis methods were applied. The results from the Soviet institutes were originally analyzed based on linear elastic K_{IC} equations whereas the VTT results were analyzed based on the elastic plastic J-integral. In order to make the results comparable, the Soviet results were corrected for the plastic zone size and the VTT results were transformed into K_J values with the equation

$$K_{JC} = \sqrt{\frac{J_C \cdot E}{(1-\mu^2)}} \tag{1}$$

where E is the modulus of elasticity and μ is the Poisson's ratio.

STATISTICAL ANALYSIS

Several factors affect the result of a fracture toughness test. Most of them can, however, be accounted for with the help of a statistical brittle fracture model (Wallin et al, 1984, Wallin, 1984, 1985, 1989a and 1989b).

The fracture toughness can either be determined using large specimens applying linear-elastic formulas or it can be derived from the elastic-plastic critical J-integral value corresponding to brittle fracture with equation (1).

Regardless whether K_{IC} or K_{JC} is used, the results can, in the case of brittle fracture, be thickness corrected with the equation (Wallin, 1985)

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

where K_{min} is the lower bound fracture toughness, which for steels is close to 20 MPa$\sqrt{m}$.

The above equation has been validated for a large number of materials and for specimen thicknesses ranging from 10 mm to 200 mm (Wallin, 1985 and Törrönen et al, 1988). The equation has even been successful in describing the behaviour of 1000 mm wide cracks with 25 mm thick specimens (Törrönen et al, 1988).

The scatter of brittle fracture toughness results can be described with the equation (Wallin, 1984)

$$P_f = 1 - \exp\left(-\left[\frac{K-K_{min}}{K_0-K_{min}}\right]^4\right) \tag{3}$$

where P_f is the cumulative failure probability at a load level K, K_0 is a specimen thickness and temperature dependent normalization parameter.

The temperature dependence of K_0 in MPa$\sqrt{m}$ can successfully be described with

$$K_0 = \alpha + \beta \cdot \exp[\epsilon \cdot (T - TK_{100MPa\sqrt{m}})] \tag{4}$$

where $\alpha + \beta$ = 108 MPa$\sqrt{m}$, $TK_{100MPa\sqrt{m}}$ is the temperature (in °C) at which the mean fracture toughness is 100 MPa$\sqrt{m}$ and ϵ is a material constant.

Experimentally it has been found that the shape of the fracture toughness transition curve is only slightly material dependent. Therefore the values of α, β and ϵ are practically material independent. This can be seen from Fig. 1 where the temperature dependence of K_0, corresponding to a specimen thickness of 25 mm, has been plotted for several different types of pressure vessel steels and welds (Wallin, 1989c). The resulting equation for the temperature dependence of K_o in MPa√m, corresponding to 25 mm thickness, can thus be written as (Wallin, 1989c)

$$K_0 = 31+77\cdot\exp\left[0.019\cdot(T-TK_{100MPa\sqrt{m}})\right] \tag{5}$$

By combining equations (2), (3) and (5), it is possible to describe the whole fracture toughness transition curve, corresponding to brittle fracture, as a function of temperature, specimen thickness and fracture probability. Thus if the fracture toughness at a certain temperature, specimen thickness and fracture probability is known, the whole fracture toughness transition curve is known.

The validity of the above equations for the present materials is checked next. Eleven 50 mm thick 3PB specimens of heat 103405 were tested at -40°C. The results are plotted in coordinates according to equation (3) in Fig. 2. If the equation is valid, the results should follow a straight line in the diagram. This is shown to be the case. Thus the theoretical equation for the scatter can be considered validated. Next, all the results were thickness corrected, by equation (2), to correspond to a specimen thickness of 25 mm, and K_o was estimated for each material and temperature. The resulting K_o-T data were then fitted by equation (5) for evaluation of $TK_{100MPa\sqrt{m}}$. All the data were then normalized with respect to this temperature and plotted in Fig. 3 together with the theoretical 5%, 50% and 95% probability limits based on equations (3) and (5). It is seen that the theoretical equations satisfactorily describe both the temperature dependence as well as the scatter of the present materials. It is also seen that the base materials and the welds show the same temperature dependence for fracture toughness. Thus, the performed analysis provides additional validation of the theoretical equations.

CVN-K_{IC} CORRELATION

Recently, a simple theoretical correlation, based on the WST model, has been developed (Wallin, 1989d). It predicts a 1:1 correlation between the $TK_{100MPa\sqrt{m}}$ and TK_{28J} temperatures, with an offset that depends on the specimen thickness. The present results have been plotted, together with data representing 143 other materials, in Fig. 4. The correlation is shown to apply well for the PWR-440 MW materials also.

The correlation can, with the aid of equations (2),(3) and (5) be developed into statistically defined reference curves with the correlation scatter included (Wallin, 1989d). Two examples of such reference curves for a 25 mm specimen thickness are shown in Figs. 5 and 6, where the present experimental results are also included. The reference curves describe the test result behaviour quite satisfactorily. An important observation is that the welds and the base materials behave similarly. Thus, the same reference curves can be applied in both cases.

Presently, there exist special reference curves for the PWR-440 MW materials (Soviet standard NAEG-7-002-86). They are divided into three categories: 1. Normal operational conditions (NOC). 2. Interrupted normal operational conditions (INOC). 3. Emergency situations (ES). The reference curves are normalized with a TK_o temperature which, in the present case, is defined as the lowest temperature where all CVN energies are larger than 48 J. Thus, the temperature is not based on the mean Charpy values but instead on the lower bound. Using a rough correlation between TK_o and TK_{28J} the standard reference curves have been plotted together with the theory based reference curves in Figs. 7 and 8. The theory based curves correspond here to a flaw width of 150 mm. The base material reference curves are presented in Fig. 7, and the weld reference curves are presented in Fig.8. It is shown that the shapes of the reference curves are quite similar in all cases. The base material reference curves are slightly more conservative than the reference curves for the welds. Both the theoretical and the standard reference curves seem to be fairly equivalent. The theoretical curves do, however, contain certain features that make them superior to the standard reference curves. Because of the statistical specimen thickness, i.e. flaw width correction, they can be applied to any flaw size, without loss in accuracy. Furthermore, they are equally well suited for base materials as well as welds, thus they are not material dependent. Finally, due to the statistical presentation of the curves, it is possible to apply the reference curves directly in probabilistic safety calculations.

SUMMARY AND CONCLUSIONS

Recent fracture toughness results obtained for five different heats of 15X2MΦA base material and two different types of welds at different temperatures have been studied in the framework of a theoretical statistical model. The following conclusions can be made:

1- The statistical WST model does describe the cleavage fracture toughness behaviour of 15X2MΦA pressure vessel steels and corresponding welds.
2- A simple correlation between $TK_{100MPa\sqrt{m}}$ and TK_{28J} is also valid for the PWR-440 MW materials.
3- The fracture toughness of the 15X2MΦA pressure vessel steels and corresponding welds can be described with theoretical statistically defined reference curves. These reference curves are especially suitable for probabilistic failure analysis.

ACKNOWLEDGEMENTS

The experimental part of this work was performed within a cooperative programme between Imatra Power Company and Atomenergoexport and financed by Imatra Power Company. The analytical part was performed within the "Structural Materials in Nuclear Power Plants" programme carried out at the Technical Research Centre of Finland and funded by the Ministry of Trade and Industry in Finland.

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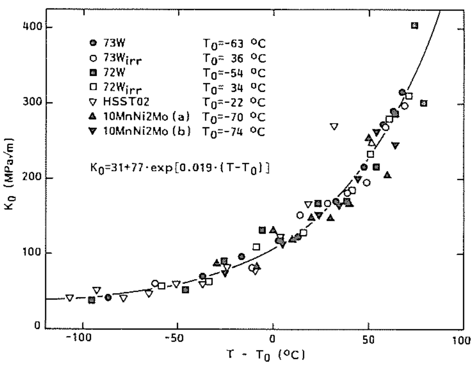

Figure 1. Temperature dependence of K_o for 25 mm specimen thickness (Wallin, 1989c).

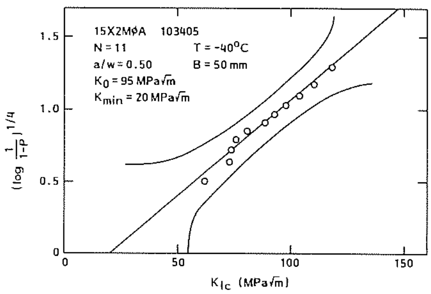

Figure 2. Failure probability diagram.

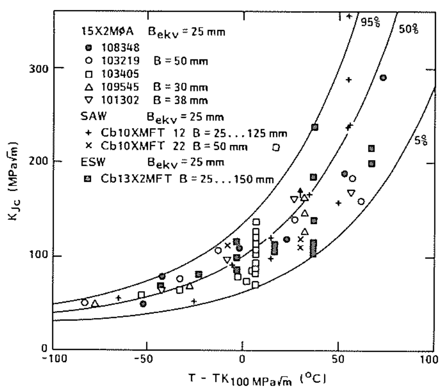

Figure 3. Normalized (25 mm) temperature dependence and scatter for PWR-440 MW materials.

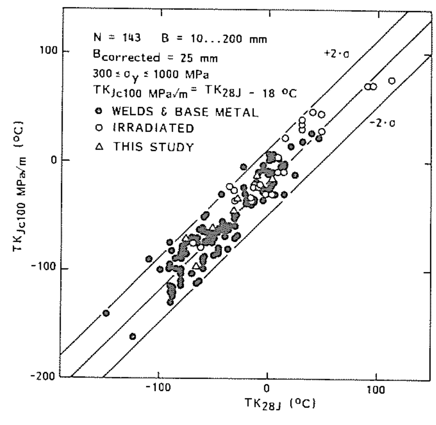

Figure 4. CVN-K_{IC} correlation for 25 mm thick specimens.

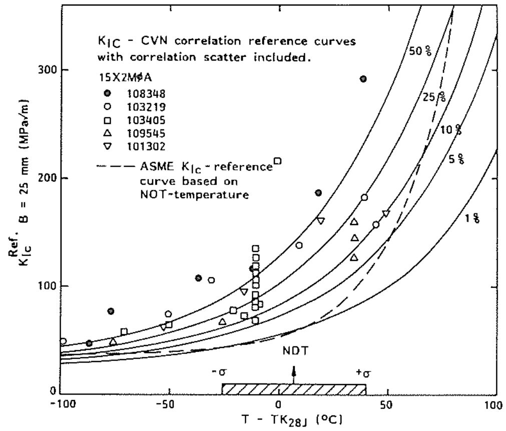

Figure 5. Fracture toughness reference curves based on CVN-K_{IC} correlation.

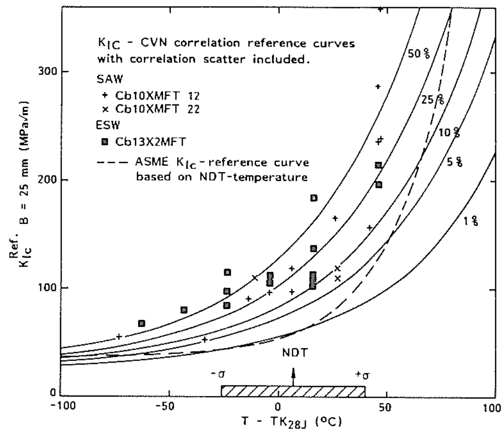

Figure 6. Fracture toughness reference curves based on CVN-K_{IC} correlation.

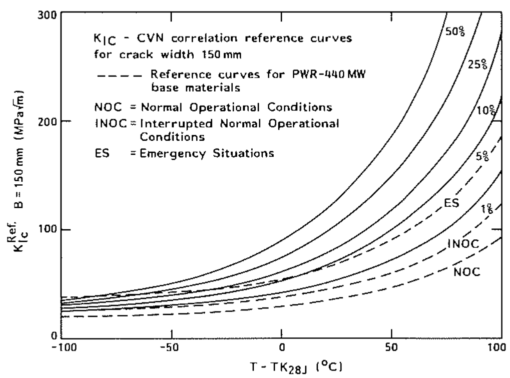

Figure 7. Comparison of statistical and standard reference curves.

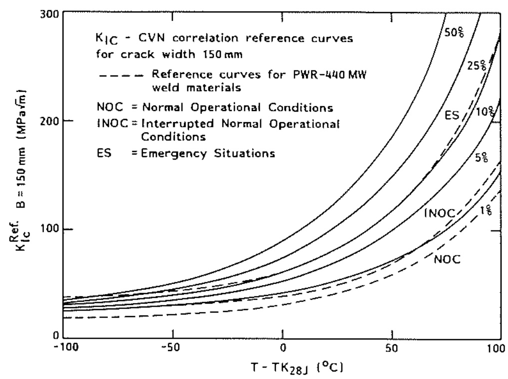

Figure 8. Comparison of statistical and standard reference curves.