SMALL SPECIMEN FRACTURE TOUGHNESS CHARACTERIZATION - STATE OF THE ART AND BEYOND

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ABSTRACT

The term fracture toughness usually refer to the linear elastic fracture resistance parameter K_{IC}. In the case of structural steels, the estimation of K_{IC} is limited to the lower shelf of toughness or require extremely large specimens. This specimen size requirement has been one major obstacle for applying fracture mechanics in structural integrity assessment outside aviation, nuclear and off-shore industries. During the last decade, a statistical data treatment methodology, based on a micomechanistic cleavage fracture model, combined with elastic plastic finite element analysis has enabled the fracture toughness to be characterized with small specimens in the ductile to brittle transition region. The development has led to a new testing standard for fracture toughness testing of ferritic steels in the transition range. Here, the premises for the methodology are described and its validity range is discussed. Presently the methodology has been validated for as small as $10 \cdot 10$ mm^2 bend specimens, but the use of even smaller specimens is under investigation.

KEYWORDS

Fracture toughness, brittle fracture, ferritic steel, small specimens, master curve, statistical treatment, VTT-method.

INTRODUCTION

Normally, 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 elastic behaviour of the test specimen or full section thickness specimens, respectively. 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. These specimen size requirements are a major obstacle for applying fracture mechanics in structural integrity assessment outside aviation, nuclear and off-shore industries. 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 approach 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 an example of the VTT approach, an irradiation damage assessment scheme, for reactor pressure vessel steels, is shortly sketched in Fig. 1.

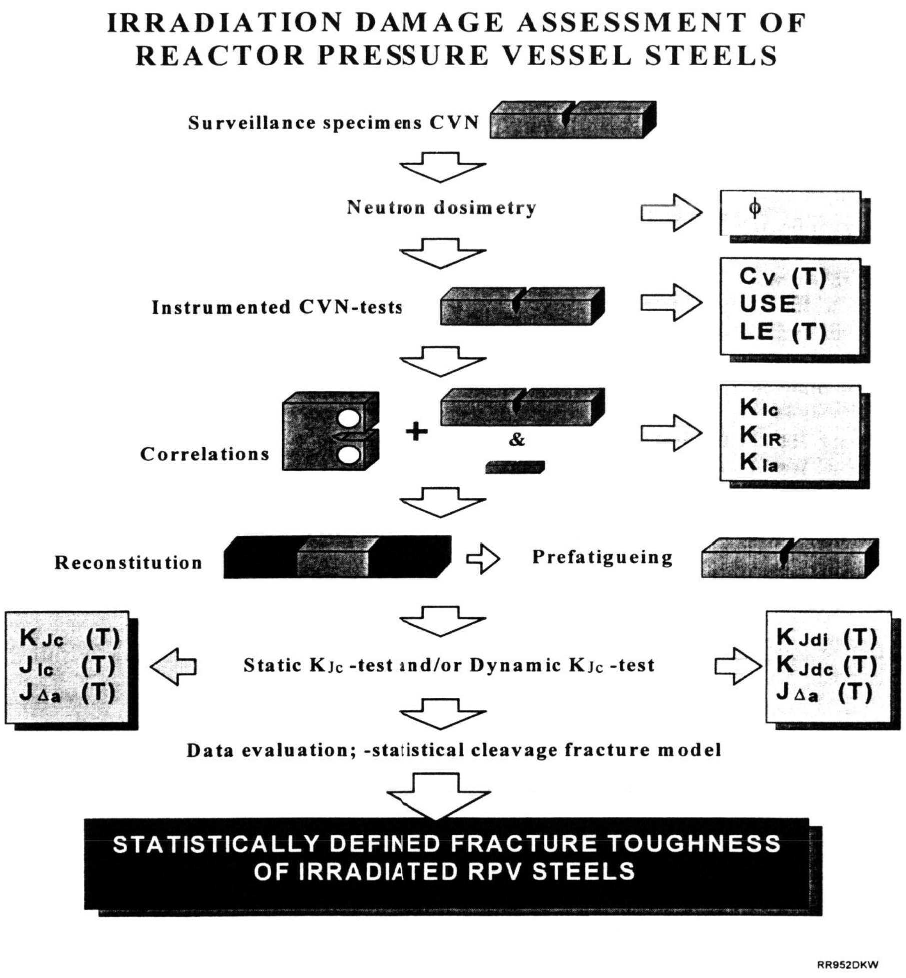

Fig. 1 The VTT approach for irradiation damage assessment.

Presently, work is under way to produce a testing standard for fracture toughness testing in the transition region (McCabe, et al., 1993). The standard is in a way "first of a kind", since it includes guidelines on how to properly treat the test data for use in structural integrity assessment. No standard, so far, has done this. The standard is based on the VTT approach. Key components in the standard are statistical expressions for describing the data scatter (Wallin, 1984) and for predicting a specimens size (crack front length) effect (Wallin, 1985) and an expression (master curve) for the fracture toughness temperature dependence (Wallin, 1991) and (Wallin, 1993a). The standard and the approach it is based upon can be considered to represent the state of the art of small specimen fracture toughness characterization. In the following, the key components in the standard and the VTT approach are outlined together with verification of their validity.

STATISTICAL ANALYSIS METHODS

The approach is based on a statistical brittle fracture model, which gives for the scatter of fracture toughness (Wallin, 1984).

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

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 predicts a statistical size effect of the form (Wallin, 1985)

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

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

On the lower shelf of fracture toughness ($K_{IC} << 50$ MPa√m) the equations may 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} (Wallin, 1993b)On the lower shelf, the initiation criterion is no longer dominant, but the fracture is completely propagation controlled (Wallin, 1993b). 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, where the use of small specimens become valuable, however, eqs 1 and 2 are valid.

For structural steels, a "master curve" describing the temperature dependence of fracture toughness has been proposed (Wallin, 1991) and (Wallin, 1993a).

$$K_0 = 311 + 77 \cdot \exp\left(0.019 \cdot \left[T - T_0\right]\right) \tag{3}$$

where T_0 is the transition temperature (°C) where the mean fracture toughness, corresponding to a 25 mm thick specimen, is 100 MPa$\sqrt{m}$ and K_0 is 108 MPa$\sqrt{m}$.

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.

Usually the separate data are analyzed directly by a combination of eqs 1-3. This is possible when all specimens fail by brittle fracture. The analysis of data sets which include results ending in non-failure, is slightly more complicated. If some of the non-failure values are lower than some of the failure values, the data set is defined as being randomly censored. Moskovic (1993) has presented a general method of analyzing randomly censored fracture toughness data sets. His method, based upon the maximum likelihood concept, is somewhat simplified when it is combined with eqs 1-3.

The maximum likelihood estimate, for a randomly censored data set, for estimating T_0 when the scatter obeys eq 1 and the temperature dependence obeys the master curve (eq 3),

$$\sum_{i=1}^{n} \frac{\delta_i \cdot \exp\left\{0.019 \cdot \left[T_i - T_0\right]\right\}}{11 + 77 \cdot \exp\left\{0.019 \cdot \left[T_i - T_0\right]\right\}} - \sum_{i=1}^{n} \frac{\left(K_{IC_i} - 20\right)^4 \cdot \exp\left\{0.019 \cdot \left[T_i - T_0\right]\right\}}{\left(11 + 77 \cdot \exp\left\{0.019\left[T_i - T_0\right]\right\}\right)^5} = 0 \tag{4}$$

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).

If all test results correspond to one single temperature, eq 4 can be simplified as to yield a maximum likelihood estimate for K_0.

$$K_0 = \left(\frac{\sum_{i=1}^{n} \left(K_{IC_i} - 20\right)^4}{r - 1 + \ln(2)} \right)^{1/4} + 20 \tag{5}$$

In eq 5, n is the total number of fracture toughness values (failed and non-failed) and r is the number of toughness values corresponding to brittle failure. Eq 5 includes also a small bias correction, which starts to have an effect when r<6. When eqs 4 and 5 are used to determine T_0, and the test temperatures are in the range T_0-50 °C...T_0+50 °C, the standard deviation of the estimate is approximately $\sigma_{T_0} \approx 17/\sqrt{r}$ °C.

VALIDITY OF K_{JC}

With small specimens, some amount of plastification is unavoidable. Therefore, it is not possible to determine the linear-elastic K_{IC}, but one is forced to determine it's elastic plastic equivalent K_{JC}. The J-integral based parameter K_{JC} is defined as,

$$K_{JC} = \sqrt{\frac{J_C \cdot E}{(1 - \nu)^2}} \tag{6}$$

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

The validity of K_{JC} has been challenged based upon the assumption that only K_{IC} represents a full plane strain stress state. However, the definition of plane strain for K_{IC} does not in reality correspond to the actual stress state in front of the crack tip. The majority of materials, used for the development of the K_{IC} standard failed by a ductile failure mechanism. In some cases the measured 95 % secant based K_Q values showed a decreasing trend, with increasing specimen size, whereas in other cases the reverse behavior was seen. A common feature for K_Q was that the specimen size dependence started to level off with increasing specimen size (an effect that is probably connected to the leveling off of the tearing resistance curve). Thus plane strain was defined as to produce approximately size independent toughness values, not minimum toughness values related to a maximum stress state.

The American Society for Mechanical Engineering (ASME) gives a reference fracture toughness curve based upon K_{IC}. The material constituting the base line results (majority) for the reference curve is an A533B Cl.1 steel plate having the designation HSST 02. The reference curve data base contain 70, HSST 02, K_{IC} values corresponding to specimen thicknesses in the range 25-275 mm. This data set is often referenced to as the *million dollar curve*. When the data is treated by eqs 2-4, the transition temperature is obtained as T_0 = -28 °C (Fig. 2).

Three, elastic plastic K_{JC} data sets, for the same material, have also been determined and are shown in the same figure. One set is part of the Electric Power Research Institute (EPRI) Nuclear Pressure Vessel Steel Data Base (Server and Oldfield, 1978) and the others are part of the Heavy Section Steel Technology Program performed at Oak Ridge National Laboratory (ORNL) (McGowan et al., 1988; Sokolov et al., 1997). Two of the data sets are based on 25 mm thick specimens, so that the use of eq 2 is not necessary. The third data set is based on pre-cracked Charpy-V specimens tested statically. The transition temperatures (eq 4) for the three data sets are respectively (Fig. 2), T_0 = -28 °C (EPRI, 25 mm CT), T_0 = -24 °C (ORNL, 25 mm CT) and T_0 = -30 °C (ORNL, 10 mm CVN_{pc}). These results give strong support to the validity of K_{JC} in respect to K_{IC}. Considering the cost of small specimen fracture toughness testing, the EPRI and ORNL data sets could probably be referenced to as *twenty thousand dollar curves*. Additional, indirect validation of K_{JC} in respect to K_{IC} has been obtained through the development of a Charpy-V - K_{IC} correlation (Wallin, 1989) where it has been shown that the correlation is the same for K_{JC} and K_{IC}.

In principle, any fracture mechanical parameter is valid as long as it gives a correct description of the stress and strain field in front of the crack tip. Thus, an elastic plastic parameter is just as valid as a linear elastic parameter, as long as it is capable of describing the stresses and strains in the fracture process zone.

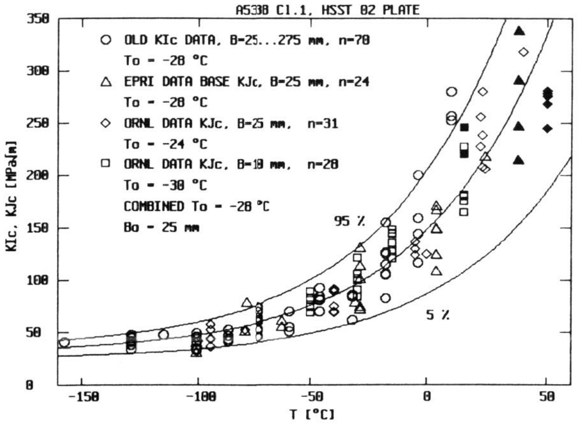

Fig. 2 Comparison between ASTM E 399 K_{IC} and it's elastic plastic equivalent K_{JC} for the ASME reference curve base line material. Filled symbols refer to non-failed, end of test, values.

Small specimens have a smaller measuring capacity than large specimens, but the elastic plastic fracture parameter itself (K_{JC}) is as valid as ASTM E399 K_{IC}.

STATE OF THE ART

The measuring capacity of bend type specimens can be expressed in the form

$$K_{JC_{limit}} = \sqrt{\frac{E \cdot b \cdot \sigma_{ys}}{M}} \tag{7}$$

where $K_{JC(limit)}$ denotes the maximum measuring capacity of the specimen, E is the modulus of elasticity, b is the ligament size and M is a constant. Classically, the thickness has assumed to be of greater importance than the ligament size, but for deeply cracked bend specimens with $b \leq B$, the ligament is really the primary dimension controlling the measuring capacity of the specimen. The significance of the specimen thickness with regard to loss of constraint, is further lowered when side-grooving the specimens (Wallin, 1995). Side-grooving, on one hand, reduce the length of the crack front, but on the other hand, it raises the stress triaxiality. The overall effect of side-grooving tend to be insignificant for normal size specimens. For small specimens it helps to uphold the constraint in the thickness direction.

Three dimensional finite element results indicate that the measuring capacity of bend specimens is limited to $M \geq 50$ (Nevalainen and Dodds, 1995), but the Master curve standard apply the slightly less restricting criterion $M \geq 30$. It is recognized that a single fracture toughness value corresponding to this M value may of the order 20 % in error. If single data were used, such an error would be unacceptable, but the standard prescribes that the analysis must be based on minimum 6 "valid" test results. This way, at least 4 or 5 results will correspond to $M \geq 50$ and the overall effect of the possible error in a single value is effectively made insignificant. This ensures the T_0 estimate to be effectively unaffected by loss of constraint.

The measuring capacity of the specimen is further obscured by the fact that in the transition region, ductile tearing often precede brittle fracture. Ductile tearing has the tendency to increase constraint and also to increase the likelihood of brittle fracture, and thus, in effect, to increase the measuring capacity of the specimen. Actually, quite often it appears that even the present size criterion ($M \geq 30$) could be somewhat relaxed. Two examples of this are presented in Figs. 3-6.

Fig. 3 show fracture toughness data for the experimental weld 73 W (Nanstad et al., 1992; Sokolov et al., 1997). All the large specimens (excepting one 25 mm specimen) produce valid test results according the new standard size criterion, but only approximately half of the Charpy-size specimens yield valid results. Still, all transition temperature estimates are exceptionally close, thus indicating no loss of constraint for the Charpy-size specimens.

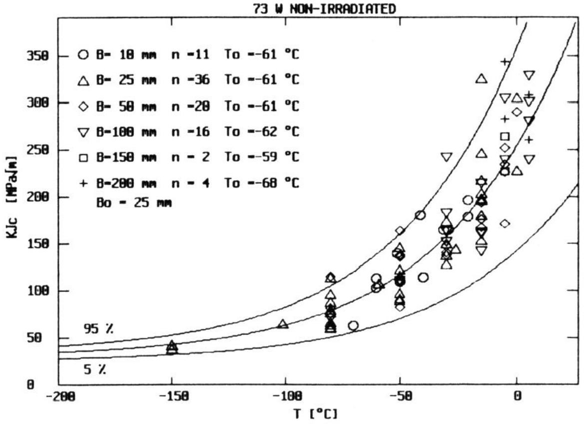

Fig. 3 Elastic-plastic fracture toughness data for weld 73 W analysed by the VTT approach. 10 mm thick specimens refer to reconstituted pre-fatigued CVN specimens manufactured and tested at VTT. The larger specimen data refer to original CT specimens tested at ORNL (Sokolov et al. 1997).

The same data was re-analyzed, censoring all the data that violated the M ≥ 30 size criterion (Fig. 4). The censoring of more than half of the small specimen data, had the effect of changing the transition temperature by only one degree, thus producing additional verification for the conservatism of the criterion M ≥ 30 for this material.

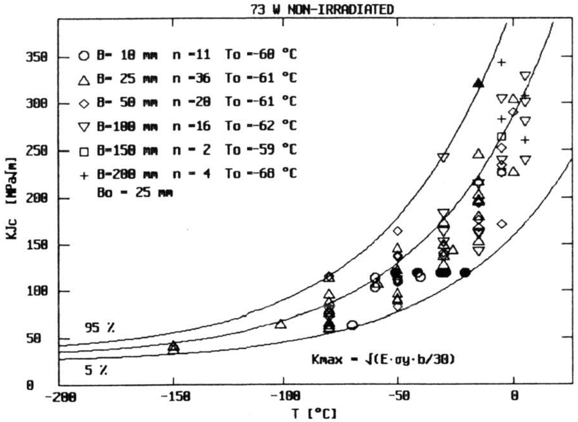

Fig. 4 Same data as in Fig. 3, but censoring all data violating the M ≥ 30 size criterion.

A data set, to be considered extreme, with regard to possibility of loss of constraint is shown in Fig. 5 (Ingham et al., 1989). The material is pressure vessel steel A533B Cl.1 having a high resistance against ductile tearing. This enabled the achievement of brittle fracture at very high temperatures in relation to the transition temperature T_0. Despite the extremely high fracture toughness values, the small and large specimens produce surprisingly similar transition temperature estimates, ranging from -115 to -107 °C. The similar behaviour of the different specimen sizes is partly explained by the fact that the larger specimens were tested at higher temperatures, thus experiencing a similar amount of loss of constraint as the small specimens. For this data the application of the M ≥ 30 size criterion has a clear, but not very significant effect.

The re-analyzed data, performing censoring for M < 30 data, is presented in Fig. 6. As to be expected, the censoring affects the small specimens results the most, but even for this highly censored case the effect on T_0 is only 6 °C. Overall, the censoring has the effect of reducing the difference between specimen sizes and is therefore beneficial for the reliability of the small specimen fracture toughness estimate.

The state of the art of small specimen fracture toughness characterization can presently be stated as to consist of Charpy-size specimens. There exists presently ample proof for that Charpy-sized specimens provide fracture toughness estimates in the ductile to brittle transition region with equivalent reliability to much larger specimens. The validity of the elastic-plastic fracture toughness equivalent K_{JC} with respect to the linear-elastic fracture toughness K_{IC} has also been confirmed.

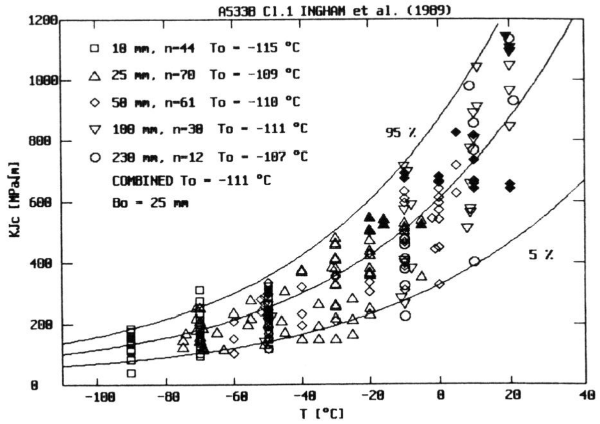

Fig. 5 Elastic-plastic fracture toughness data for pressure vessel steel A533B Cl.1 analysed by the VTT approach. All data refer to square section bend specimens (Ingham et al., 1989).

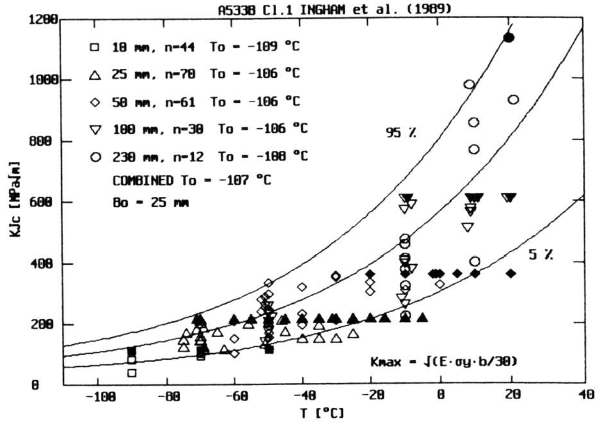

Fig. 6 Same data as in Fig. 5, but censoring all data violating the M ≥ 30 size criterion.

The size of material samples needed for fracture toughness testing can furthermore be reduced by applying specimen reconstitution techniques. With simple stud welding teqhnique it is possible to manufacture Charpy-sized specimens for fracture toughness testing from 10x10x15 mm samples (Valo and Ahlstrand, 1993). Actually, test results indicate that even 10x10x10 mm samples can be used, but that cannot be considered to be within the present state of the art. More validation work is needed before so small reconstitution samples can be used with confidence.

BEYOND STATE OF THE ART

The Charpy-size specimen may be considered to be a miniature specimen from the point of fracture toughness testing, but for some applications even a material sample of 10x10x15 mm may prove to be too large. Then, one is forced to go beyond the state of the art to even smaller specimen sizes. One solution may to some appear to lie in correlating fracture toughness to some other parameter determined from a small material sample. This, however, cannot be considered to be anything more than a qualitative solution, not applicable for any real structural integrity assessment. Another solution might consist of connecting the correlation with micromechanical modelling. A number of approaches, based on this concept have popularly been named the "*local approach*". Presently, however, the local approach models are so crude that they should not be used for any real quantitative predictions of the fracture toughness. The solution remaining is to apply the master curve approach to even smaller specimens and to quantify the specimens measuring capacity more accurately.

It should be quite simple to reduce the specimen size in half, by reducing the thickness to 5 mm. For a deep cracked bend specimen, a square ligament causes the measuring capacity to be controlled primarily by the ligament and not the thickness, especially if the specimens are side-grooved. To check this hypothesis, Charpy- and half-Charpy-specimens, of A533B Cl.1 plate, were tested at VTT (Nevalainen et al., 1996). The results, analysed by the Master curve approach, are presented in Fig. 7. The result is very promising in that both the specimen types yield the same transition temperature to within 5 °C, the smaller specimens yielding the more conservative estimate.

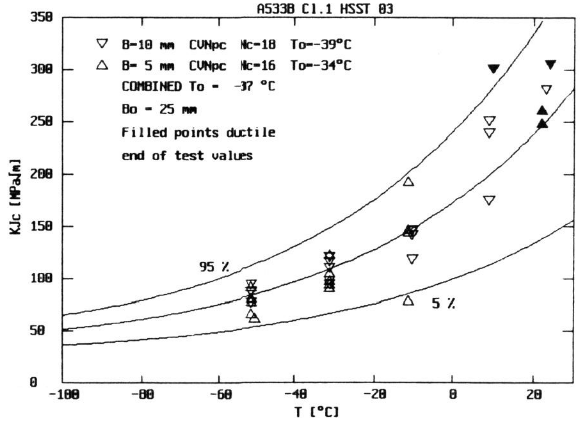

Fig. 7 Elastic-plastic fracture toughness data for pressure vessel steel A533B Cl.1 analysed by the VTT approach (Nevalainen et al., 1996).

In an effort to examine the applicability of even smaller specimens a second data set, including additionally specimens with a 3x4 mm cross-section (KLST-specimens). The material was a ferritic stainless steel with designation ”F82H modified”. The results, analysed by the Master curve approach, are presented in Fig. 8 (Nevalainen et al., 1996). The results are somewhat confusing, in that there is a large difference between the behaviour of the 10 mm and 5 mm thick specimens. The difference could be contributed to a smaller measuring capacity of the 5 mm specimens, were it not for the fact, that the behaviour of the 3 mm thick specimens indicates less loss of constraint than the 5 mm thick specimens. The reason for the contradictory behaviour is still under investigation and hopefully turns out to be a material inhomogeneity effects. Clearly, the applicability of KLST type specimens for fracture toughness estimation looks promising, but much more work, both experimental as well as analytical is needed before anything conclusive regarding their use can be stated.

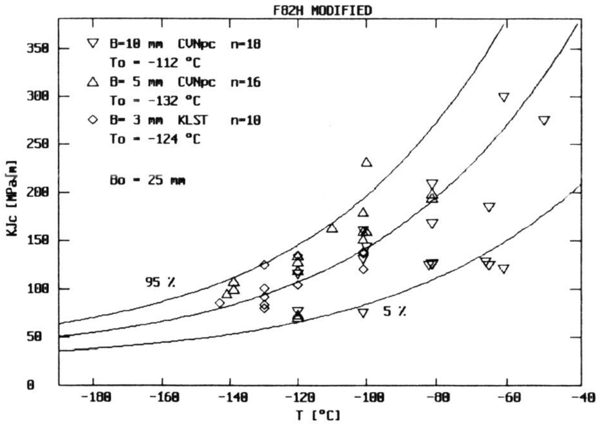

Fig. 8 Elastic-plastic fracture toughness data for ferritic stainless steel F82H modified analysed by the VTT approach (Nevalainen et al., 1996).

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