GUIDELINES FOR DERIVING FRACTURE TOUGHNESS ESTIMATES FROM NORMAL AND MINIATURE SIZE CHARPY-V SPECIMEN DATA

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Abstract

Modern structural integrity assessment relies upon fracture mechanics, thus utilizing fracture mechanical parameters describing the materials fracture resistance. However, fracture mechanical material properties are usually difficult and expensive to determine. Instead, the material properties are usually described by more simple parameters, like those determined by the Charpy-V impact test. Unfortunately, presently applied empirical correlations between Charpy-V and fracture toughness are quite unreliable.

In this paper, a theoretical approach is applied to derive a commonly applicable CVN-K_{IC} correlation. The existence of a theoretical correlation is verified both for linear-elastic and elastic-plastic data. Factors affecting the applicability of the correlation are discussed. Furthermore, guidelines for treating also subsize and miniature Charpy-specimens are presented.

1 INTRODUCTION

Important parameters for the assessment of critical structures are different fracture mechanical parameters which are capable of describing a components resistance against flaws. One frequently applied parameter is the fracture toughness K_{IC}. In case of structural steels it usually describes the materials resistance against brittle cleavage type fracture. However, the determination of K_{IC} is relatively expensive as well as difficult. Therefore there have been attempts to determine the value of K_{IC} from simpler tests through the application of empirical correlations.

The most common simple test for studying the fracture characteristics of steels is probably the Charpy-V impact test. Therefore, most of the empirical fracture toughness correlations that have been developed are between Charpy-V energy and fracture toughness K_{IC}. Numerous different empirical correlations have been determined for a variety of materials, over the past years [2]. A total of 21 different empirical correlations have been discussed in Ref. [8] and most recently, The Welding Institute (TWI) is even marketing a software package consisting of 25 different published empirical correlations.

Finding an empirical correlation that would be universally applicable has proven to be quite difficult. This is depicted by Fig. 1, taken from Ref. [8]. Fig. 1 includes both so called upper shelf correlations as well as so called transition region correlations. It turns out that it is practically impossible to classify the correlations according to material type, toughness level or even fracture mode. One should bear in mind that, even though both tests describe the materials fracture behaviour, they have differences. The most important differences between Charpy-V and K_{IC} tests are presented in Table 1.

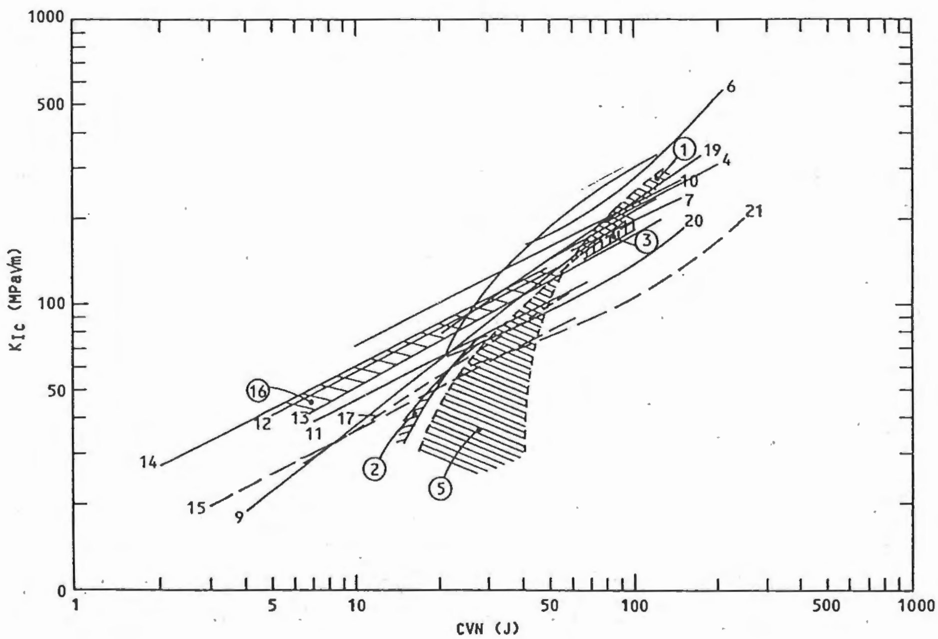

Fig. 1. Comparison of different published empirical Charpy-V - K_{IC} correlations [8].

Due to the differences in the tests the empirical correlations are not only material dependent [2,6], but also test performance dependent. Therefore, it is practically impossible to decide which empirical correlation is optimum in a given case.

The use of empirical correlations is further obscured by the fact that the impact tests are often performed with subsize and miniature specimens. Presently, hardly any published correlation covers also subsize and miniature specimens.

Table 1. Differences between CVN and K_{IC} tests.

DIFFERENCE	CVN	K_{IC}
Specimen size	10·10·55	$B > 2.5 \cdot (K_{IC}/\sigma_y)^2$
Loading rate	dynamic	static
Flaw geometry	short blunt notch	deep crack
Event described in test	fracture initiation + propagation	fracture initiation

In this paper, a theoretical approach is applied to derive a commonly applicable CVN-K_{IC} correlation. The effects of the differences in the tests are minimized with a theoretical examination of each difference. The treatment is performed by applying a statistical micromechanism based cleavage fracture model. The existence of a theoretical correlation is verified both for linear-elastic and elastic-plastic data. Factors affecting the applicability of the correlation are discussed. Furthermore, guidelines for treating also subsize and miniature Charpy-specimens are presented.

2 CHARPY-V - K_{IC} CORRELATION

Based on Table 1 it is clear that one cannot unambiguously correlate the impact energy directly with the fracture toughness. One must first clarify which parameters are realistic to correlate. In order to do this the basic features of each test must be examined separately to see which features are the same.

2.1 K_{IC} TEST

Several factors affect the result of a fracture toughness test. Many of them can, however, be accounted for with the help of a statistical brittle fracture model [13].

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

$$K_{JC} = \sqrt{E \cdot J} \quad . \tag{1}$$

Regardless whether K_{IC} or K_{JC} is used, the results can, in the case of brittle fracture, be thickness corrected with [7]

$$K_{B_2} = (K_{B_1} - K_{min}) \cdot (B_1/B_2)^{1/4} + K_{min} \quad , \tag{2}$$

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

Eq. 2 has been validated for a large number of both low and high strength structural steels and for specimen thicknesses ranging from 10 mm to 200 mm. Even though definitive proof of a statistical model is very difficult, the successful application of the model for more than 100 materials might be considered as a comparatively strong validation.

If the linear-elastic K_{IC} is used, it is important that the specimen has actually behaved fully linearly. If one is forced to apply the so called secant method because of plasticity and if invalid K_Q-values are obtained, the values will be overly conservative for that specimen thickness. In such cases it is better to use the elastic-plastic K_{JC} to develop the correlation.

The scatter of brittle fracture toughness results can be described by [6]

$$P_f = 1 - \exp(-\left(\frac{K_I - K_{min}}{K_0 - K_{min}}\right)^4) \quad , \tag{3}$$

where P_f is the cumulative failure probability at a stress intensity factor level K_I and 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 [11]

$$K_0 = \alpha + \beta \cdot \exp[\gamma \cdot (T - T_0)] \quad , \tag{4}$$

where $\alpha + \beta = 108$ MPa$\sqrt{m}$, T_0 is the temperature (in °C) at which the mean fracture toughness is 100 MPa$\sqrt{m}$ and γ is a material constant.

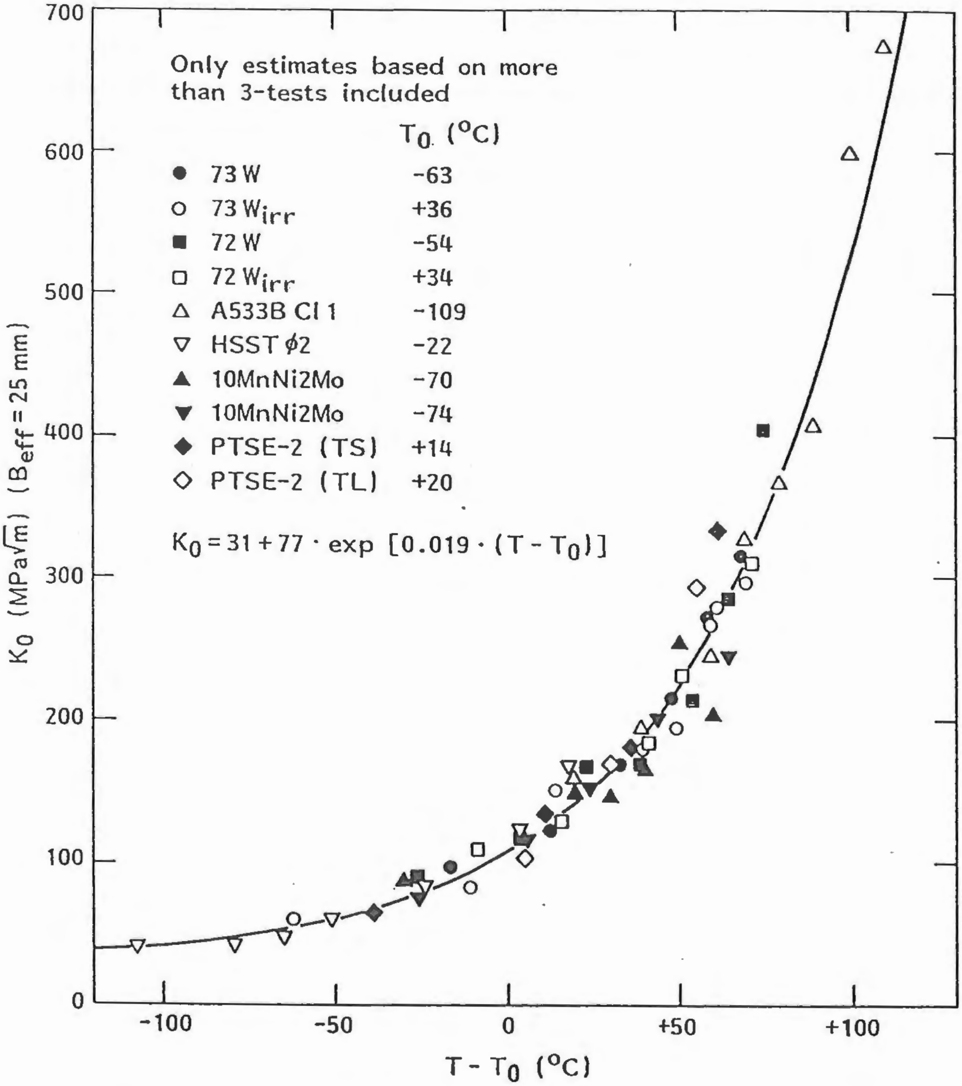

Fig. 2. Temperature dependence of K_0 for 25 mm specimen thickness [11].

Experimentally it has been found that the shape of the fracture toughness transition curve for steels is only slightly material and yield strength dependent [11]. Therefore the values of α, β and γ are practically material independent. This can be seen from Fig. 2 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. The resulting equation for the temperature dependence of K_0, corresponding to 25 mm thickness, can thus be written as [11]

$$K_0 = 31 + 77 \cdot \exp [0.019 \cdot (T - T_0)] . \tag{5}$$

By combining Eqs. 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.

From the fracture toughness point of view it is thus recommendable to choose for the correlation a temperature corresponding to a certain fracture toughness describing brittle fracture. The chosen temperature must be clearly below the fracture toughness for ductile fracture initiation so that ductile fracture will not affect the result. At the same time it must be clearly higher than the lower shelf in order to be in a region where the effect of temperature upon toughness is large. One commonly used transition temperature fulfilling these demands is the temperature corresponding to $K_{JC} = 100$ MPa$\sqrt{m}$.

2.2 CHARPY-V TEST

If temperature is chosen as the parameter to correlate in the K_{IC} test, it also has to be chosen in the Charpy-V test. The chosen temperature must, in addition to fulfilling the same requirements as in the case of K_{IC}, correspond to a low enough energy so that the impact energy value will not depend on the applied testing standard. Also, because ductile crack growth is not allowed, a temperature corresponding close to the lower shelf must be chosen. On the other hand, the chosen temperature should correspond to the increasing part of the transition curve and it is also recommendable to choose a commonly recognized energy-level. One such temperature is the transition temperature corresponding to Charpy-V impact energy 28 J. This temperature is also equivalent to the temperature used by Marandet & Sanz [1] in their empirical correlation which did not consider the effects of the test differences theoretically.

The chosen impact energy level is practically independent of testing standards and at this energy level the amount of ductile tearing is small. The differences in specimen sizes can be accounted for in the fracture toughness. Remaining, strongly affecting, factors are the effect of the blunt notch and the effect of loading rate difference.

An increasing loading rate shifts the toughness transition to higher temperatures and the magnitude of the effect is inversely related to the materials yield strength. A blunter notch on the other hand shifts the toughness transition to lower temperatures. Also in this case the magnitude of the shift is inversely related to the materials yield strength. This is because the "singular" loading experienced by a crack is directly related to the strain hardening exponent and inversely related to the yield strength. A high strength material having a small strain hardening exponent does not "see" such a large difference between a crack and a blunt notch. Even though neither difference can accurately be accounted for, their effects are of the same magnitude and opposite to each other. Their combined effect can therefore be expected to be quite small.

Based on the theoretical treatment, the temperatures TK_{28J} and $TK_{100MPa\sqrt{m}}$ were selected for correlation [6,7]. First a basic correlation was determined. The fracture toughness data used to determine the basic correlation had to fulfil two requirements. All results were to be based on elastic plastic K_{JC} results, in order to avoid plasticity effects, and they had to be obtained with test specimens of the same thickness. An often used specimen thickness in elastic-plastic testing is 25 mm (1T) so a thickness of 25 mm was chosen for the basic correlation. Results from 141 materials fulfilling the requirements were analyzed. The major part of the data refers to different heats of reactor pressure vessel steels (A508 Cl.3 and A533B Cl.1) and their welds, but many different types of steels are represented. The yield strengths of the materials vary from 300 to 1000 MPa, with most of them in the range 400 - 600 MPa, and the upper shelf energies vary between 60 - 250 J. Furthermore, some irradiated materials are included. The obtained correlation is presented in Fig. 3.

The correlation has the form

$$TK_{100MPa\sqrt{m}} = TK_{28J} - 18\ °C \tag{6}$$

and it's standard deviation is σ = 15 °C.

Remarkable with the correlation is that the yield strength of the material does not seem to have a statistically significant effect. This finding is consistent with the theoretical considerations. Thus the correlation is equally applicable for both low and high strength steels.

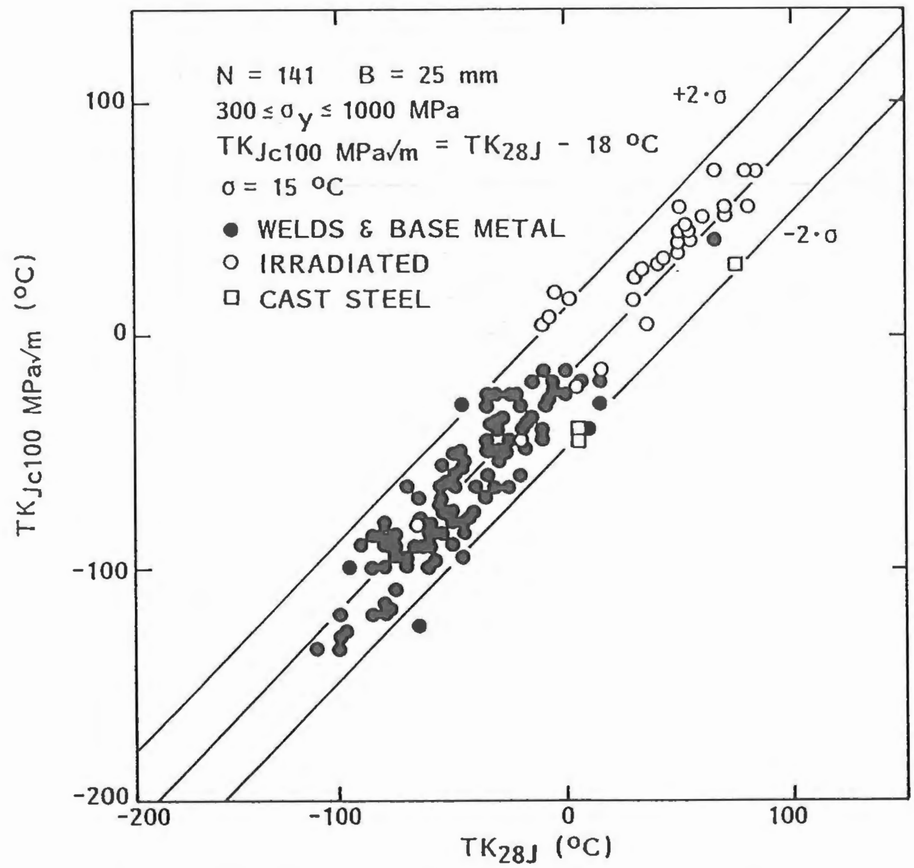

Fig. 3. Basic CVN-K_{IC}-correlation for 25 mm thick specimens.

The next step was to verify the correlation also for data obtained from specimens with thicknesses other than 25 mm. A total of 150 materials with elastic-plastic results from varying size specimens (B = 10 - 200 mm) were analyzed. Again the materials yield strengths were in the range 300 - 1000 MPa. The fracture toughness data was size corrected with Eq. 2 to correspond to 25 mm thickness. The thickness corrected results are presented in Fig. 3 together with the mean and ±2·σ lines as obtained from the basic correlation. It is seen that the basic correlation describes the thickness corrected data well.

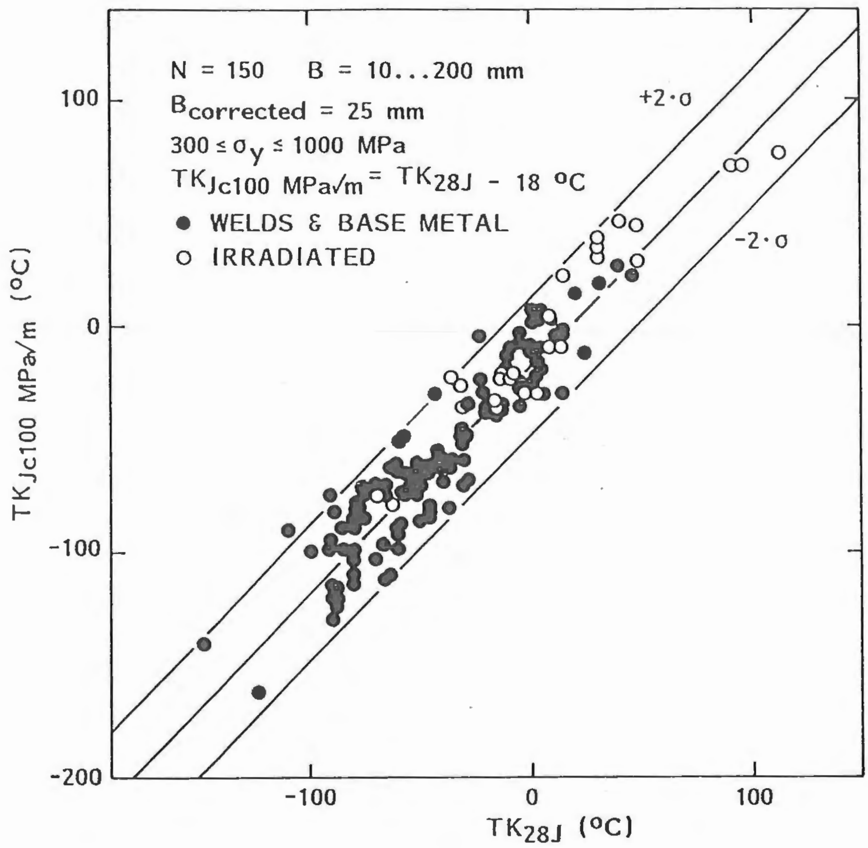

Fig. 4. CVN-K_{IC}-correlation for thickness corrected elastic-plastic fracture toughness.

Finally, the correlation was checked for linear-elastic K_{IC} data. In Fig. 5, linear elastic results for 72 materials have been presented together with the mean and $\pm 2\cdot\sigma$ lines as obtained from the basic correlation. The data has again been thickness corrected with Eq. 2 to correspond to 25 mm thickness. The actual specimen thickness is in the range 25 - 250 mm and the yield strength is in the range 400 - 1500 MPa, but the basic correlation is valid also for this data. In Fig. 5, invalid K_Q results are included. Because these invalid results yield overly conservative fracture toughness results for the specific thickness, this will also affect the correlation and it is seen that the K_Q results would produce a slightly differing correlation.

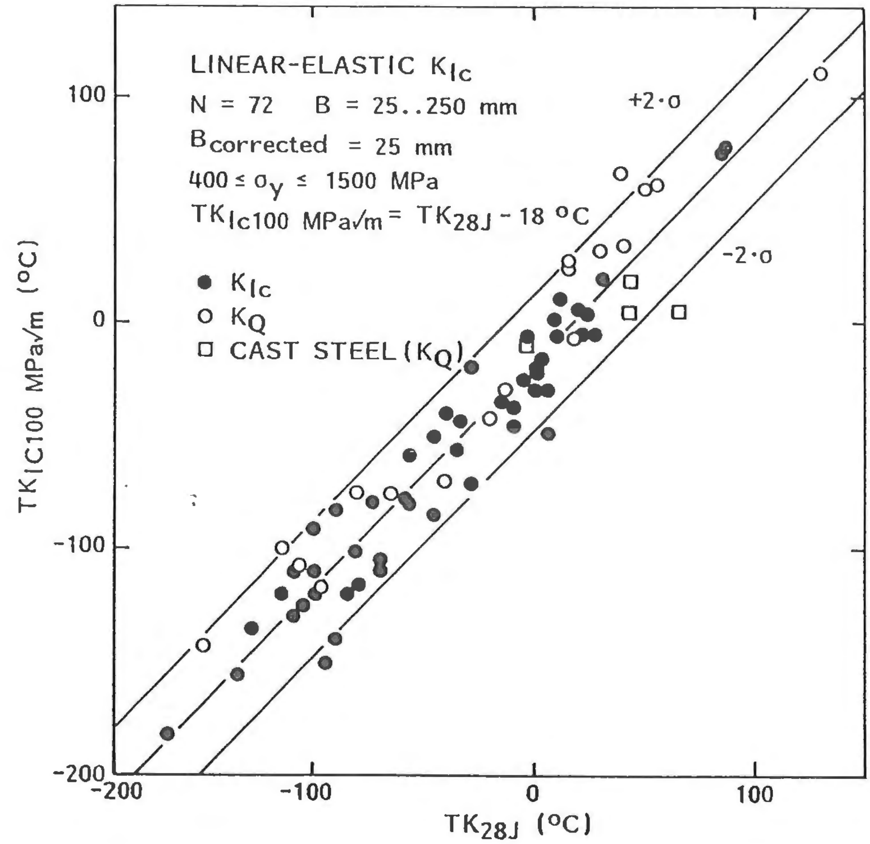

Fig. 5. CVN-K_{IC}-correlation for thickness corrected linear-elastic fracture toughness.

The standard deviation consists of three independent standard deviations:

- $\sigma_{TK\ 100MPa\sqrt{m}}$ = standard deviation of temperature $TK_{100MPa\sqrt{m}}$
- $\sigma_{TK\ 28J}$ = standard deviation of temperature TK_{28J}
- $\sigma_{corr.}$ = standard deviation of correlation.

The combined standard deviation can thus be divided into parts as

$$\sigma = \{\sigma^2_{TK\ 100MPa\sqrt{m}} + \sigma^2_{TK\ 28J} + \sigma^2_{corr.}\}^{1/2} = 15\ °C\ . \tag{7}$$

It is possible to determine the standard deviation in the fracture toughness transition temperature estimate theoretically by applying eg. Monte Carlo simulation combined with Eqs. 3 and 5. Assuming the fixed shape of the transition curve and fitting only the temperature yields

$$\sigma_{TK\ 100MPa\sqrt{m}} \approx \frac{18\ °C}{\sqrt{N}} \tag{8}$$

where N is the number of specimens used to determine the transition temperature.

In most cases of the data presented in Figs. 3 - 5, the number of tests, in the cleavage fracture region, varied between 5 and 10. Because the fracture toughness transition temperature was determined with assuming the fixed shape of the transition curve, the standard deviation of the fracture toughness temperature estimate becomes 5 - 8 °C. When this figure is extracted from the total standard deviation the effective standard deviation of the correlation is obtained as

$$\sigma_{eff} = \{\sigma^2_{TK\ 28J} + \sigma^2_{corr.}\}^{1/2} \approx 13\ °C\ . \tag{9}$$

The main contributor to the effective standard deviation is of course the uncertainty in the correlation itself. $\sigma_{corr.}$ is a complex function of the material yield strength, strain hardening properties, upper shelf energy value and temperature. The correlation could be improved by accounting for all these factors, but then the simplicity of the correlation would be lost.

The basic correlation can be modified to describe the whole fracture toughness transition curve by making use of Eq. 5. The fracture toughness can thus be expressed as a function of the Charpy-V transition temperature

$$K_{IC} = 20+\{11+77\cdot\exp(0.019\cdot[T-TK_{28J}+18°C])\}\cdot\left(\frac{25}{B}\right)^{1/4}\cdot\left(\ln\frac{1}{1-P_f}\right)^{1/4} \tag{10}$$

where TK_{28J} includes the correlation scatter and has the standard deviation 13 °C. It has to be emphasized that when applying equation (10) to surface flaws, B (in mm) does not correspond to the material thickness but the flaw width 2·c.

3 CVN SUBSIZED AND MINIATURE SPECIMENS

When the plate thickness is less than 10 mm, testing with standard sized Charpy-V notch specimens is impossible. In such cases the testing must be based on subsized specimens. The difficulty lies in extrapolating the result from the subsized specimen to correspond to the result from a standard sized specimen. Basically two different methodologies can be used. The extrapolation can be based either directly upon the measured parameter e.g. impact energy KV or on some transition temperature criterion.

The ideal situation would be to be able to extrapolate directly the impact energies from subsized specimens to correspond to standard size specimens. Unfortunately, even though some simple equations for the purpose have been developed [6], they are not as reliable as one could desire. The problem with direct extrapolation lies in the fact that the specimen thickness yield different effects in different regions of the transition. On the lower shelf subsized specimens yield proportionally higher impact energies as compared to standard size specimens. On the upper shelf the behaviour is reversed so that subsized specimens yield either proportionally equal or even lower impact energies than standard sized specimens [9-11]. The reason for this is that the different fracture micromechanisms yield different specimens thickness effects. In the transition region there is a competition between ductile and brittle fracture micromechanisms thus yielding a very complex combined thickness effect. A much more reliable extrapolation can be obtained by considering some transition temperature criterion.

The Charpy-V - K_{IC} correlation is for the Charpy-V test based on the 28 J (35 J/cm^2) impact energy level transition temperature. It is thus logical to apply an equivalent transition criterion also for the subsized specimens. From a fracture mechanical point of view, the natural choice is constant absorbed energy per fractured surface. This leads to a criterion based on the 35 J/cm^2 transition temperature. Unfortunately the criterion is not specimen size independent. It is affected both by the constraint effect as well as the statistical thickness effect. Both effects act in the same direction so that a subsize specimen will yield a lower transition temperature than a standard size specimen. Thus subsized specimens must be penalized to fulfil the criterion at a lower temperature than would be required for standard size specimens. If the constraint effects are predominant the thickness effect upon the transition temperature should be dependent on the materials yield strength. An earlier investigation looking at different transition criteria [6] indicate that this is not necessarily the case.

In order to determine the effect of specimen thickness upon the transition temperature TK_{35J/cm^2}, data from the literature corresponding to a variety of steels were collected [12]. The materials corresponded to strength levels in the range 200 - 1000 MPa and specimen thicknesses in the range 1.25 -20 mm. The study was, however, limited to specimen thicknesses between 3 and 10 mm, because this thickness range is most relevant for normal applications. From the data the difference in transition temperature (ΔT), as compared with the standard specimen size, was determined for the different specimens thicknesses. The data was then fitted by least square sum estimation with [12]

$$\Delta T_i + \varepsilon_i = \zeta \cdot \ln\{\, 2 \cdot (B_i/10)^{\xi} - 1\} \tag{11}$$

where ζ and ξ are fitting constants defining the thickness dependence and ε_i is the estimated error in each individual standard specimen size transition temperature. The value of ε_i was selected for each data set so as to yield the smallest standard deviation in the overall fit. Due to the nature of the procedure the standard deviation of ε_i will slightly overestimate the true error, whereas the standard deviation of the total fit (which also describes the error in individual temperature determinations) should slightly underestimate the true fit. The fitted data is presented in Fig. 6 [12].

The standard deviation of the total fit ($\sigma_{\Delta T}$) is 4.4 °C and the standard deviation of the error parameter (σT_{10}) is 4.9 °C. The result indicates that the fitted equation is capable of describing the thickness effect on the transition temperature. It also implies that the true standard deviation of the individual error in the transition temperature determination is approximately 4.5 °C. Because this error is already included in the Charpy-V - K_{IC} correlation (Eq. 10) it is sufficient to apply the curve corresponding to the mean ie.

$$\Delta T = 51.4 \cdot \ln\{2 \cdot (B/10)^{0.25} - 1\} \quad (°C)\,. \tag{12}$$

From Fig. 6 it is seen that Eq. 12, even though not developed for thicknesses below 3 mm, yields a good description of the thickness dependence all the way down to a thickness of 1.25 mm. Such thicknesses should however be treated with caution, because they lie outside the fitting range of the equation.

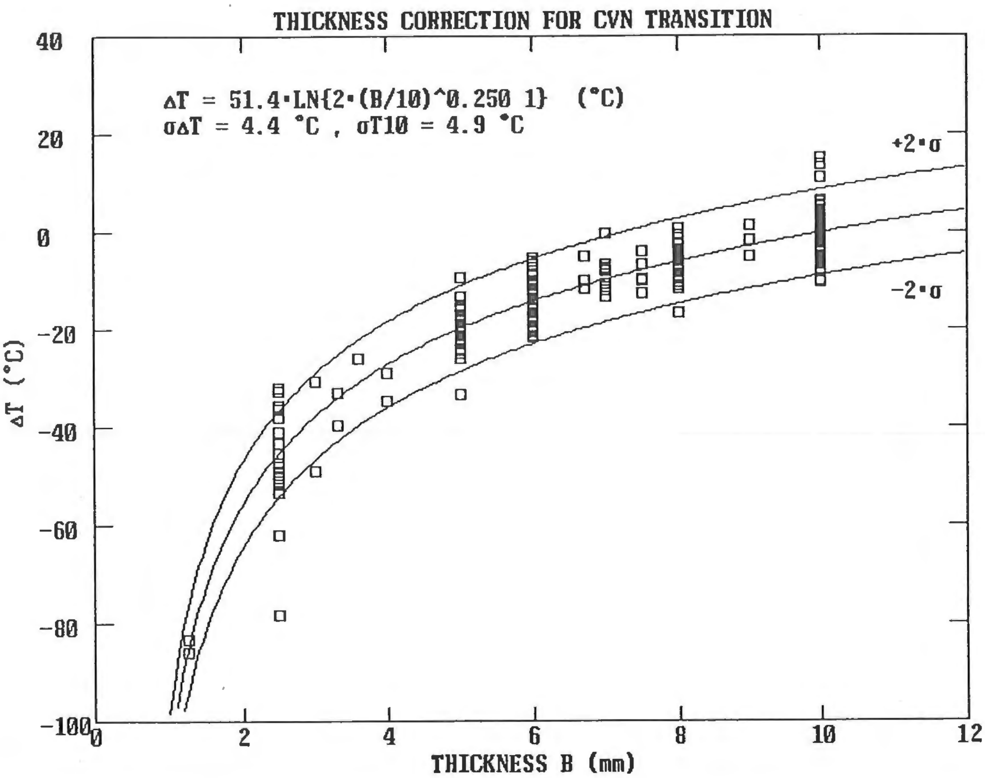

Fig. 6. Effect of specimen thickness upon Charpy-V notch transition temperature corresponding to the energy level 35 J/cm^2. Material yield strengths in the range 200 - 1000 MPa.

Miniature specimens where practically all dimensions (including notch geometry) are reduced or altered, are not as reliable as subsize specimens where only the specimen thickness is reduced. However, using a fracture mechanical analogy, the analysis of existing miniature specimen data, indicate that Eq. 12 is applicable also for miniature size specimens [12]. The analysis performed so far, have, however, been quite limited. Thus the application of Eq. 12 for miniature specimens should be treated by somewhat caution.

Occasionally, the transition temperature corresponding to another energy level is known instead of the one corresponding to the equivalent of 28 J. In order to make use of the correlation presented here, such a transition temperature must be corrected to correspond to the 35 J/cm^2 transition temperature. The shape of the Charpy-V transition curve is a complex function of different parameters, but a satisfactory description of the curve can be obtained by considering the two main parameters (yield strength and upper shelf energy). The following equation has been proposed [6]

$$T\text{-}TK_{35J/cm^2} = 21.6 \cdot \{\frac{\sigma_y}{467}\}^{0.56} \cdot \ln\{\frac{KV(KV_{US}\text{-}35J/cm^2)}{35J/cm^2(KV_{US}\text{-}KV)}\} \quad . \qquad (13)$$

Eq. 13 was originally developed for standard sized specimens, but it can be applied also in the case of subsized specimens when the impact energy level in question is not very far from 35 J/cm^2.

4 RESTRICTIONS

The Charpy-V - K_{IC} correlation is based upon cleavage fracture. Thus the correlation should not be used for steels with upper shelf energies below 70 J/cm^2 or where the brittle fracture mode is something else than cleavage fracture (eg. grain boundary fracture, low energy tear etc.). The correlation should neither be used for strongly inhomogeneous materials which may show a so called pop-in behaviour in the fracture toughness test [6]. In such cases it is impossible to determine the fracture toughness from the Charpy-V test and therefore actual fracture toughness testing is required.

5 SUMMARY

Guidelines to determine the fracture toughness from impact test results has been presented. The guidelines which are based on a statistical correlation between fracture toughness and Charpy-V, are applicable for all ferritic structural steels. In the following the guidelines are summarized.

The fracture toughness can be expressed as a function of the Charpy-V transition temperature

$$K_{IC} = 20+\{11+77\cdot\exp(0.019\cdot[T\text{-}TK_{28J}+18°C])\}\cdot(\frac{25}{B})^{1/4} \cdot (\ln\frac{1}{1\text{-}P_f})^{1/4} \qquad (10)$$

where TK_{28J} includes the correlation scatter and has the standard deviation 13 °C. When applying Eq. 10 to surface flaws, B (in mm) does not correspond to the material thickness but the flaw width 2·c.

For subsized and miniature Charpy-V specimens the transition temperature TK_{35J/cm^2} (equivalent to TK_{28J}) should be determined. The use of a smaller specimen yields a penalty which is expressed as

$$\Delta T = 51.4 \cdot \ln\{2 \cdot (B/10)^{0.25} - 1\} \quad (°C) . \tag{12}$$

If the transition temperature corresponding to another energy level is known instead of the one corresponding to the equivalent of 28 J, such a transition temperature must be corrected to correspond to the 35 J/cm² transition temperature. The following equation can be used

$$T\text{-}TK_{35J/cm^2} = 21.6 \cdot \{\frac{\sigma_y}{467}\}^{0.56} \cdot \ln\{\frac{KV(KV_{US}\text{-}35J/cm^2)}{35J/cm^2(KV_{US}\text{-}KV)}\} \tag{13}$$

With the above procedure it is possible to determine the fracture toughness for all structural steels showing a ductile/brittle transition behaviour.

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