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Sub-sized CVN specimen conversion methodology

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Abstract

Presently most structural integrity assessment procedures still allow the use of Charpy-V notch impact tests as a measure of fracture toughness. The use is generally made through some more or less reliable correlations between standard Charpy-V notch energy and fracture toughness or tearing resistance. A problem arises if the structure has such a geometry that standard size Charpy-V notch specimens cannot be used. Application standards contain some guides on how to convert sub-sized specimen data to correspond to full size specimens, but these are often inaccurate and limited in their application range. Procedures like ASTM A370, BS7910 and API 579 give some advice on the use of sub-sized Charpy-V specimens but none of them cover the whole Charpy-V transition curve. Here, a new simple procedure, that is in line with BS7910, is presented. It is shown that it is applicable over the whole transition curve, thus enabling a point-wise conversion of sub-sized Charpy-V data to correspond to full size specimens. The new procedure is applicable for steel strengths ranging from 200 MPa to 1400 MPa.

Keywords: Charpy-V; sub-size specimen; transition curve, fracture

1. Introduction

Presently most structural integrity assessment procedures still allow the use of Charpy-V notch (CVN) impact tests as a measure of fracture toughness. The use is generally made through some more or less reliable correlations between standard CVN energy and fracture toughness or tearing resistance. A problem arises if the structure has such a geometry that standard size CVN specimens cannot be used. E.g. when the plate thickness is less than 10 mm,

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testing with standard full-sized CVN notch specimens is impossible. In such cases the testing must be based on sub-sized or miniature specimens. Sub-sized specimens are those where the specimen thickness is reduced, but the other dimensions, including the notch, are kept constant. Miniature specimens are specimens where all dimensions are reduced, including the notch geometry. Both specimen types are recognized by different impact test standards, but no testing standard gives advice about the meaning of test results determined by such specimens.

Nomenclature

B	Specimen thickness
CVN	Charpy-V notch
FCC	Face Centered Cubic
KV	Charpy-V impact energy
KV_{US}	Upper shelf energy
T	Temperature
T_{28J}	Transition temperature corresponding to 28 J impact energy
T_{35J/cm^2}	Transition temperature corresponding to 35 J/cm^2 impact energy
$\sigma_{\Delta T}$	Standard deviation of temperature difference

The difficulty lies in converting the result from the sub-sized or miniature specimen to correspond to the result from a standard sized specimen. Basically two different methodologies can be used. The conversion 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 sub-sized or miniature specimens to correspond to standard full-size specimens. In several manufacturing standards, sub-sized specimens are correlated to full-sized specimen by a simple constant multiplier on the energy. Sometimes, the same proportional energy is simply required for sub-sized specimens. This requirement is often but not always also combined with a temperature compensation. Many codes require a higher proportional impact energy for sub-size specimens, but without a temperature compensation. Specifically, for a 5x10 mm^2 specimen, usually the energy is multiplied by 1.5 to make it correspond to a full-size specimen. The problem with the direct extrapolation lies in the fact that the specimen thickness yields different effects in different regions of the transition range. This is highlighted in Fig. 1 where 5 mm sub-sized specimen energy is compared with full-size specimen energy, Wallin et al. (2002).

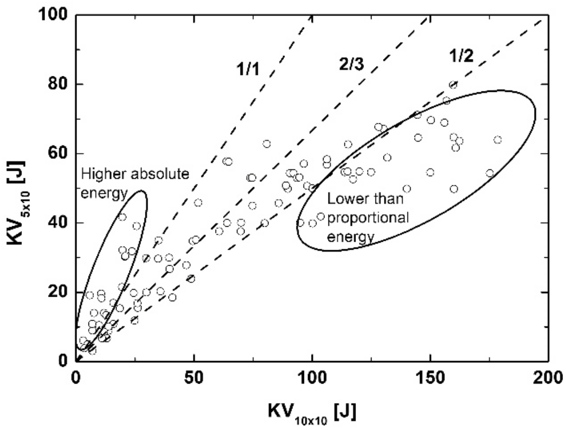

Fig. 1. Example of impact energy relations between sub-sized (5x10 mm) and full-sized (10x10) CVN specimens. Data taken from Wallin et al. (2002).

On the lower shelf sub-sized specimens yield proportionally higher impact energies as compared to standard size specimens. They may even produce higher absolute energies than a full size specimen. On the upper shelf the behavior is reversed so that sub-sized specimens yield either proportionally equal or even lower impact energies than standard sized specimens. The reason for this controversial behavior 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. This effectively invalidates the method of direct extrapolation which is commonly used today. In the case of miniature specimens, the correlation is even more difficult, since in this case, also the notch geometry usually changes from case to case.

The problem is highlighted in Fig. 2 which shows transition curves for different thickness sub-sized specimens, McNicol (1969). Two things are apparent. First, the ductile-to-brittle transition is moving to lower temperatures with decreasing specimen thickness. Second, the proportional upper shelf energy is reduced with decreasing specimen thickness.

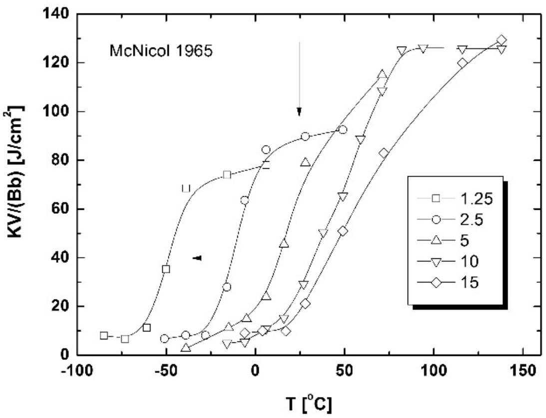

Fig. 2. Effect of specimen thickness (mm) on proportional Charpy-V impact energy as a function of temperature. Data taken from McNicol (1969).

Because of the problem with a direct energy correlation, usually the best correlations between different specimen types are based on some transition temperature criterion.

Application standards contain some guides on how to convert sub-sized specimen data to correspond to full size specimens, but these are often inaccurate and limited in their application range. Procedures like ASTM A370, BS7910 and API 579 give some advice on the use of sub-sized CVN specimens but none of them cover the whole CVN transition curve.

Here, a new simple procedure, which is in line with BS7910, is presented. It is shown that it is applicable over the whole transition curve, thus enabling a point-wise conversion of sub-sized CVN data to correspond to full size specimens. The new procedure is applicable for steel strengths ranging from 200 MPa to 1400 MPa.

2. The procedure

2.1. Transition temperature

The brittle fracture is affected both by a constraint effect as well as a statistical thickness effect. Both effects act in the same direction so that a sub-size specimen will yield a lower transition temperature than a standard full-size specimen. Thus sub-sized specimens must be "penalized" to fulfil the criterion at a lower temperature than would be required for standard full-size specimens. If the constraint effects are predominant, the thickness effect upon the transition temperature should be dependent on the materials yield strength. On the other hand, if the statistical size effect is predominant, yield strength should not affect the thickness effect.

In order to determine the effect of specimen thickness upon the 35 J/cm² transition temperature (T_{35J/cm^2}), data from the literature corresponding to a variety of steels have been assessed by Wallin (1994). The materials corresponded to yield strength levels in the range 200-1000 MPa and specimen thicknesses in the range 1.25-20 mm. The analysis was limited to specimen thicknesses between 3 and 10 mm, because this thickness range is most relevant for brittle fracture assessment. From the data the difference in transition temperature (ΔT), as compared with the standard full-size specimen size, was determined for the different specimen thicknesses. The fitted data is presented in Fig. 3.

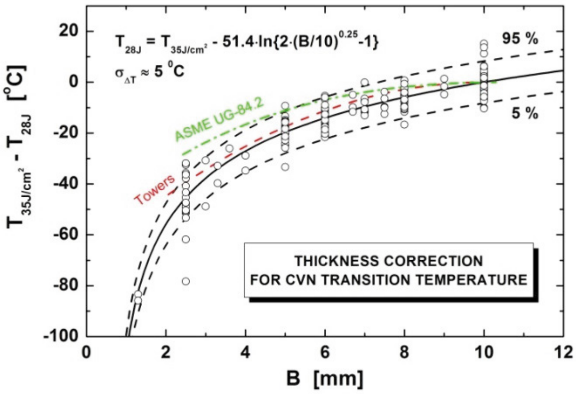

Fig.3. Effect of specimen thickness on the 35 J/cm2 CVN transition temperature. Data taken from Wallin (1994).

The mean thickness dependence has the form of Eq. (1).

$$\Delta T_{35J/cm^2} = 51.4°C \cdot ln\left\{2 \cdot \left(\frac{B}{10\ mm}\right)^{0.25} - 1\right\} \quad (1)$$

The yield strength was shown to have a negligible effect upon the thickness dependence in the thickness range 3-10 mm. This indicates that the main contribution to the thickness effect, at this energy level, comes from the statistical size effect. From Fig. 3 it is seen that Eq. (1), 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.

Fig. 3 includes also two other relations for the effect of specimen thickness on the transition temperature. The relation by Towers (1986) is nearly equivalent to Eq. (2) in the thickness range 3…10 mm, which was the focus of the Towers work. The difference between the Towers relation and Eq. (2) is mainly that Eq. (2) is based on a much larger data base. The ASME UG-84.2 relation, that is also included in e.g. ASTM A333 and API 579, is much older and its background is not known. Based on the available data, The UG-84.2 relation is non-conservative and should not be used.

2.2. Upper shelf energy

As shown in Fig. 2, sub-size CVN specimens on the upper shelf absorb the same or less amount of energy per area as normal size CVN specimens. Fig. 4 shows a compilation of 88 data sets from Wallin (2001). Each data set contained standard 10 mm thick CVN upper shelf data and data for various sub-sized (B = 2.5-9 mm) and/or over-sized (B = 20 mm) specimens. Many materials had data belonging to different orientations (T-L, T-S, L-T and L-S) The majority of materials were structural steels, with yield strengths in the range 244 MPa to 975 MPa. Additionally, the database contained three stainless steels, two Al-Bronzes and one aluminum. The data refers both to ASTM and ISO impact hammers. The CVN upper shelf energies covered the range from about 20 J to 300 J and showed practically no dependency on the materials yield strength.

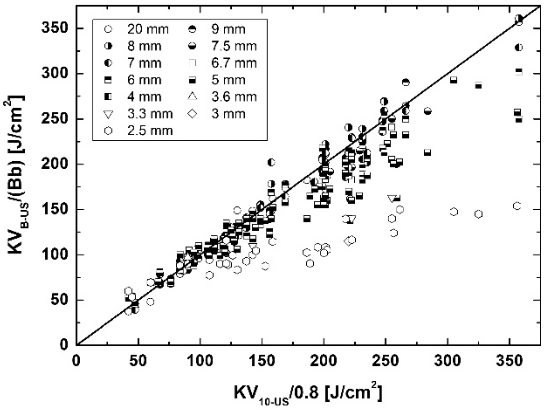

Fig. 4. Relation between sub-size and full-size CVN upper shelf energies. Data taken from Wallin (2001).

The reason for the size effect is related to shear lips. When a Charpy-V specimen fractures by ductile tearing, part of the fracture surface (middle part) will constitute of "flat" fracture and part (sides) of shear fracture regions. When the crack starts to grow, the shear regions (lips) start to develop. Their size increases with crack growth and saturates towards a thickness that is dependent on the tearing resistance of the material. This shear lip development is largely independent of specimen thickness. This means that the proportional amount of shear lips on the fracture surface will increase with decreasing specimen size. Below a certain thickness, the whole fracture surface will show shear fracture. Since the energy absorbed in the fracture process is different for flat fracture and shear fracture, reducing the specimen thickness will lead to a transformation from flat fracture description to shear fracture description.

Intuitively one would expect the yield strength and strain hardening to have an effect on the way the shear lips develop. To check this, the materials with yield strengths below 300 MPa were compared with the behavior of the materials with yield strengths above 900 MPa (Fig. 5). Somewhat surprisingly, the yield strength (and thus the strain hardening) does not have a noticeable effect on the shear lip development. It may be that the increasing yield strength, together with decreasing strain hardening capability produce two counteracting effects on the through thickness stress distribution, thus producing close to a zero combined effect. This would be understandable since high yield (flow) strength limits deformation, but low strain hardening promotes shear localization.

The fracture energy for 100% shear fracture is only about half of the energy for normal ductile tearing. This is consistent with the differences between tensile and shear flow properties and elastic properties. The description of the data requires thus a sigmoidal equation going from 1 to 0.5. In order to develop a quantitative description of the upper shelf energy relation, all the data corresponding to steels, were normalised by $KV_{10\text{-}US/B}$ and simply fitted by a hyperbolic-tangent equation, resulting in the form shown in Fig. 5 and Eq. (2), Wallin (2001).

$$\frac{KV_{B-US}\cdot 10}{KV_{10-US}\cdot B} = 1 - \frac{0.5\cdot\exp\left\{\frac{2\cdot\left(\frac{KV_{10-US}}{B}-44.7\right)}{17.3}\right\}}{1+\exp\left\{\frac{2\cdot\left(\frac{KV_{10-US}}{B}-44.7\right)}{17.3}\right\}} \quad \ldots \quad [J, mm] \tag{2}$$

The equation apparently has one basic flaw. For a specimen thickness of 10 mm, the right hand side of the equation does not become unity. This is, however, not really a flaw, but a result of the physical meaning of the equation. The equation does not directly relate the toughness of one specimen to the other, but relates the toughness affected by shear lips to a case with no effect of shear lips. Thus, the equation can also be used to examine the effect of shear lips on a standard full-sized specimen and it can be used to estimate an upper shelf energy value corresponding to 0% shear lips.

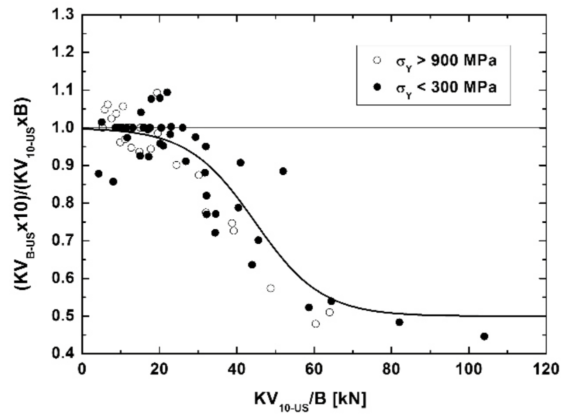

Fig. 5. Yield strength seen not to affect the size effect between sub-size and standard full-size CVN specimens. Data taken from Wallin (2001).

The above equations are valid for steels. It was found that, even though the yield strength does not affect the relation, the material's modulus of elasticity has a clear effect. The modulus of elasticity affects mainly the loading parameter $KV_{10\text{-}US/B}$. The smaller the material's modulus of elasticity, the stronger the effect of $KV_{10\text{-}US/B}$ will be. This means that the formation of shear lips is promoted by elastic flexure of the specimen. The effect is clear, even though a physical reason for it is unclear. It seems that the shear elasticity module controls somehow the shear localization of a material. This again, may be due to a connection between shear modulus and available glide systems in the material. The effect is best accounted for, by adjusting the loading parameter $KV_{10\text{-}US/B}$ with the ratio of the modulus of elasticity for steel and the modulus of elasticity for the material.

2.3. Conversion methodology

The conversion consists simply of using Eq. (2) for each individual test result, over the whole transition region and to adjust each individual test temperature with Eq. (1). Accounting for shear lip effects also in 10 mm thick specimens mean that Eq. (2) needs to be used twice. First, estimate the 10 mm thick specimen without shear lips ($KV_{10planar}$) iteratively with Eq. (2) and then use this value to estimate the energy for the 10 mm thick specimen with side grooves. As an example of the outcome of the conversion, the data in Fig. 2 were analyzed as described above. The result of the conversion is shown in Fig. 6. With the exception of the 1.25 mm thick specimens the conversion works extremely well. The behavior of the thin specimens is due to that very thin specimens develop 100 % shear lips early and thus reduce the transition region. This, however, generally has a significant effect only on specimen thicknesses below 3 mm.

3. Verification

In order to verify the procedure also for ultra high strength steels, two ultra high strength steels were tested. The steels were 10 mm thick Optim™ 960 QC (σ_y = 1090 MPa) and Weldox™ 960 (σ_y = 1016 MPa) manufactured by SSAB Europe. These steels were tested in the T-S orientation to ensure a uniform microstructure along the crack front. The sub-sized specimens had a thickness of 6 mm. The converted 6 mm data is present together with the full size data in Fig. 7. Considering the natural scatter in Charpy-V test results, the conversion provides an excellent result. It is important to use an orientation where the notch and subsequent crack lies in identical microstructures for both specimen types. Often orientations T-L or L-T are used. In this case the through thickness toughness variations may affect the result and indicate misleading size effects.

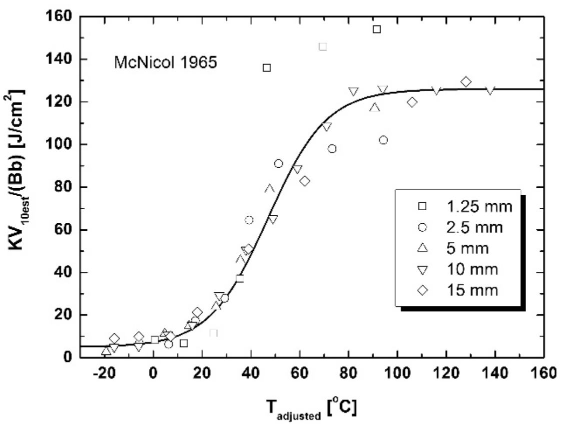

Fig. 6. Example of energy conversion for individual specimens. Data taken from McNicol (1969).

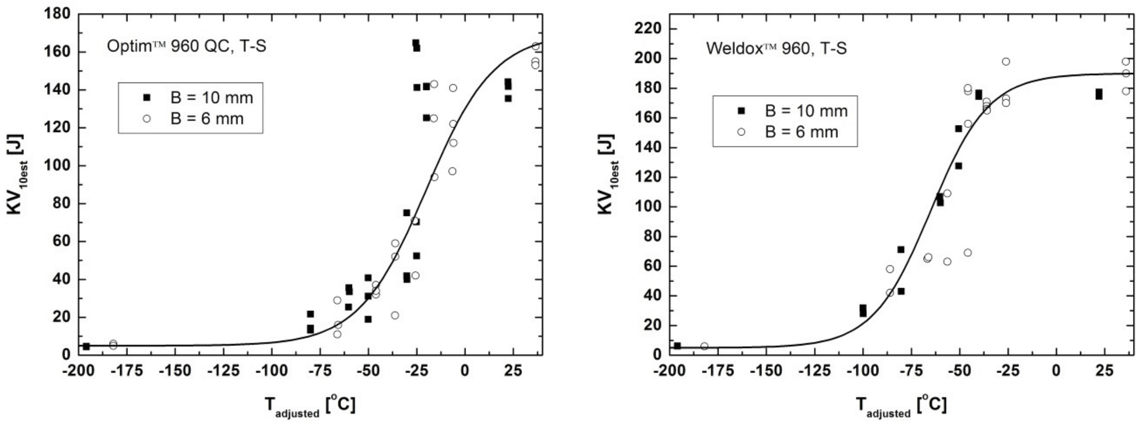

Fig. 7. Example of energy conversion for individual specimens for ultra high strength steels.

4. Discussion and conclusions

The presented methodology provides the first simple reliable conversion of sub-sized to full size specimen CVN energies. The value compared to previous methods is that it is applicable over the whole transition region and provides a single value conversion, unlike a transition temperature adjustment or upper shelf correction. Many of the previous attempts to develop corrections for sub-sized specimens have been clouded by a lack of distinguishing between different fracture micromechanisms. Also, it is of utmost importance that the different specimens correspond to the same microstructure. Often, when specimens are taken in T-L or L-T orientations, the full size and sub-size specimens may correspond to different depths from the plate surface and this may cause apparent different relations between the specimens.

The conversion methodology is not affected by the materials yield strength. It is thus equally applicable to all classes of structural steels showing a ductile to brittle transition. FCC metals that do not fail by cleavage, obviously are not affect by the temperature adjustment. For these materials, however, Eq. (2) needs to be adjusted for modulus of elasticity as described in Wallin (2001).

The conversion methodology is summarized in Fig. 8. It provides a simple graph for the energy conversion and a table for the temperature adjustment.

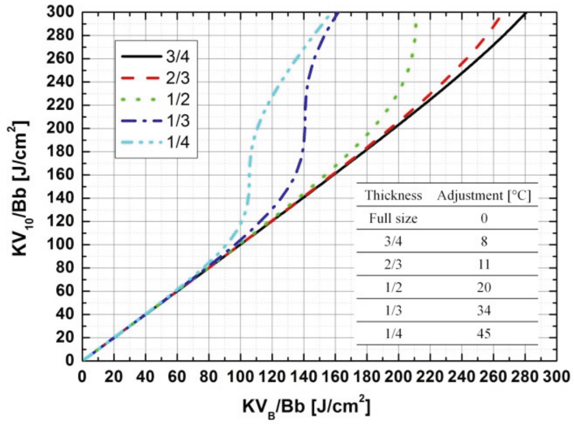

Fig. 8. Energy and temperature conversion graph for different thickness CVN specimens.

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