Int. J. Pres. Ves. & Piping **55** (1993) 203–212

A Closer Look at Estimation of Fracture Toughness from Charpy V-Notch Tests

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ABSTRACT

Although it is well known that the adequate parameters to characterise the toughness of materials are those according to the theory of fracture mechanics, the classical Charpy fracture energy is still often used in testing practice. Many efforts have been made to correlate these two types of toughness parameters with each other. In many cases these correlations give no satisfying results. In this paper it is investigated under what circumstances such correlation can exist and what type they are of. It is shown—from a theoretical point of view—that correlations are restricted to certain families of materials, i.e. that there are no general applicable correlation formulas. For those purposes the standard Charpy tests have to be replaced by instrumented tests on sharp notched or pre-cracked specimens.

1 INTRODUCTION

For decades, the charpy-V-notch (CVN) fracture energy was the most important parameter to characterise the toughness of structural metals. Even in material testing practice of today, the simple CVN test is—in spite of its limited physical basis and possibilities of application—still often used and the toughness requirements of many engineering design standards are still based on it. On the other hand, the development of fracture mechanics during the last 30 years has led to additional, physically better defined and theoretically better founded toughness parameters, the most important thereof being the fracture toughness

Int. J. Pres. Ves. & Piping 0308-0161/93/$06·00

K_{Ic}, the critical J-integral J_c and the critical crack-tip opening displacement (CTOD), δ_c. Unlike the CVN fracture energy, the fracture mechanics material parameters are independent on the geometry of the test specimens and transferable to real structures, being therefore of wider use. Many design codes and failure assessment concepts of today (e.g. safe-life or fail-safe design,[1] R-6 failure assessment method[2]) are based on these fracture mechanics material properties.

A problem which often arises when fracture mechanics concepts ought to be applied is the lack of the relevant material parameters—especially when older structures have to be assessed. In many of such cases the CVN-energies are the only available data related to toughness. For these reasons many efforts have been made during the last 20 years to estimate K_{Ic} or J_c (in this report we do not distinguish between J_c and J_{Ic}) from CVN data. Many correlation formulas have been suggested.[3–6] However, sometimes very poor agreement between values which are estimated by means of such correlation formulas and exact values is found. For example very large deviations have been found in the case of old bridge steels as wrought iron.[7,8] This casual unreliability of these correlation formulas gave reason for the closer look at the relation between CVN and fracture mechanics data, which is reported in the following.

2 EXPERIMENTAL CORRELATION BETWEEN CVN AND J_c

According to Refs 3–6 correlations between CVN and J are most likely of the form

$$J_c = qA_{vus} \tag{1}$$

where A_{vus} is the upper-shelf CVN fracture energy and q an empirical constant with the dimension mm^{-2}. According to eqn (1), A_{vus} is meant to be proportional to J_c, or, by the fundamental relation $J_c = K_{Ic}^2(1 - \nu^2)/E$, proportional to the square of K_{Ic}. In Fig. 1, some experimental data of different steels concerning this dependence are shown. They indicate, that a general unique correlation between the two parameters hardly exists. If there are correlations at all, they are obviously restricted to certain families of materials. In the following the corresponding physical reasons or theoretical explanations are explored. Furthermore, a simple method for evaluating toughness values from instrumented Charpy test is suggested.

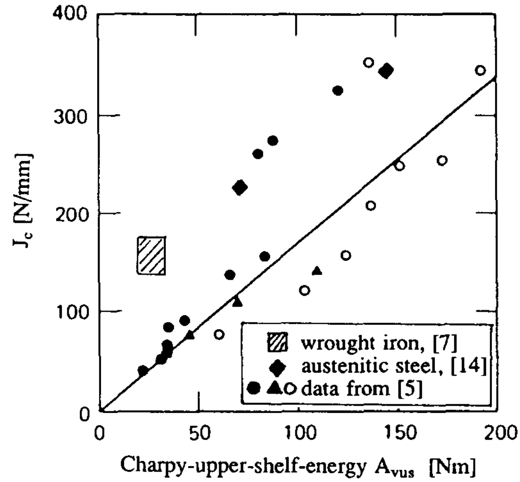

Fig. 1. Comparison of some J_c versus A_{vus} with data from Ref. 5.

3 CRACK-TIP PARAMETERS

The response of a sharp notch or a crack (notch with zero root radius ρ) on mechanical load is plastic opening displacement δ (Fig. 2). In a first stage this opening is caused by large plastic strains which produce an increased root radius (blunting) and, thereby, a certain amount of crack prolongation Δa. If the critical notch opening displacement δ_{cn} is reached, processes of fracture occur at the notch root which make the crack propagate by tearing. During tearing crack-growth, δ increases as shown schematically in Fig. 2. In general, the curve of δ in function of crack-length Δa ('R-curve') is approximately linear in Δa by the relation

$$\delta_{cn} = \delta_{0n} + \mathrm{CTOA}\,\Delta a \tag{2}$$

CTOA denotes the so-called crack tip opening angle, which is more or less independent on the root radius ρ.[9,10] The process of tearing crack-growth may be interrupted by the onset of clevage fracture, which results in a sudden decrease in CTOA. If no cleavage occurs during the complete fracture process, the fracture is called 'upper-shelf'.

In the left-hand part of Fig. 2 the behaviour of the critical notch opening displacement in it is shown in function of the notch root radius ρ. According to Refs 10 and 11 this function is linear and given by

$$\delta_{cn} = \delta_c + c_1 \varepsilon_f \rho \tag{3}$$

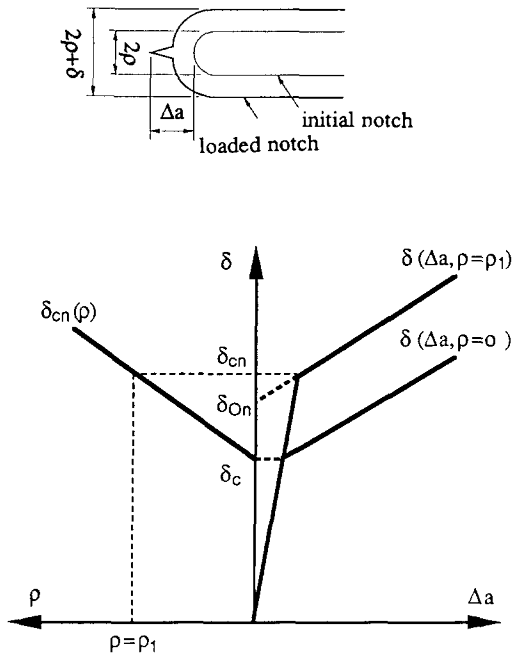

Fig. 2. Definition of δ, Δa and ρ and behaviour of δ in function of Δa and ρ (schematic).

where δ_c denotes the critical opening of a crack (i.e. a sharp notch with $\rho = 0$), ε_f the true fracture strain of the material in the neck of a tensile test specimen and c_1 a nondimensional constant of the order of 1.

The geometrical crack-tip parameters δ_c and CTOA are considered to be the primary parameters characterising the state of load of a crack or a notch. In this sense, J_c and K_{Ic} are derived crack-tip parameters, which are related to δ_c by

$$J_c = m\sigma_f\delta_c \tag{4}$$

$$K_{Ic} = [m\sigma_f\delta_c E/(1 - \nu^2)]^{1/2} \tag{5}$$

Herein, m denotes a non-dimensional factor ranging roughly from 1 (plane stress) to 2·5 (plane strain), σ_f the flow stress (which may be approximated by the mean value of the yield stress and the ultimate tensile stress), E, Youngs modulus and, ν, Poissons ratio.

4 THEORETICAL RELATION BETWEEN J_c AND CVN-FRACTURE-ENERGY

The fracture energy U_f of notched or pre-cracked three-point bend specimens which, in the case of Charpy specimens ($\rho = 0{\cdot}25$ mm,

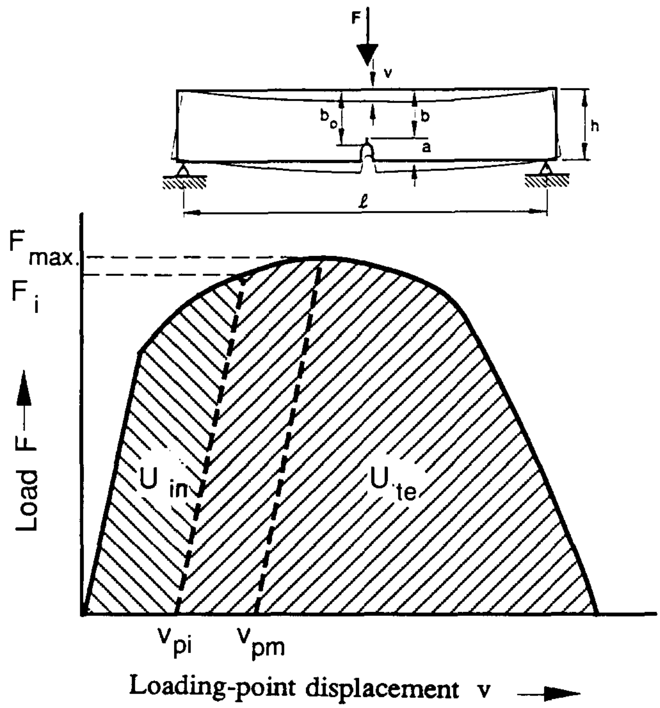

Fig. 3. Load–displacement curve and definition of U_{in} and U_{te}.

$b_0 = h - a_0 = 8\,\text{mm}$, $t = 10\,\text{mm}$), is equal to the CVN-upper-shelf fracture energy, is given by the area under the corresponding load–displacement diagram (Fig. 3). It consists of the plastic energy U_{in} which is absorbed up to the point of crack initiation and the energy U_{te} consumed during crack propagation, thus

$$U_f = U_{in} + U_{te} = U_i + U_n + U_{te} = A_{vus} \tag{6}$$

U_i is the energy corresponding to crack-initiation at a pre-existing crack, which is given by

$$U_i = J_c b_o t/2 \tag{7}$$

where t is thickness.[12] The second term in eqn (6), U_n, describes an additional term accounting for the effect of finite root radius ρ and the third, U_{te}, the energy consumed during crack-propagation. They both represent the work of the moment M at the fracturing section done on the relative rotation of the two opposite fracture surfaces, which is given by the angle θ (Fig. 4). Equation (3) implies, that U_n can be

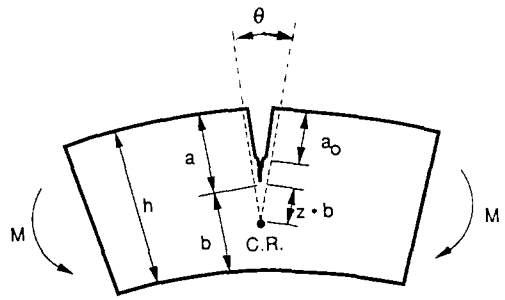

Fig. 4. Definition of parameters characterizing the fracturing section in bending.

approximated by

$$U_n = c_1 \varepsilon_f \rho M(b = b_0)/(zb) \tag{8}$$

Correspondingly, U_{te} is given by

$$U_{te} = \int_{\theta_0}^{\theta_c} M \, d\theta \tag{9}$$

where θ_0 and θ_c denote the rotational angle at the onset of tearing crack-growth and at the end of the fracture process, respectively. The bending moment M is approximated by

$$M(b) = c_2 \sigma_f t b^2/4 \tag{10}$$

where c_2 ranges from 1 (plane stress) to 1·45 (plane strain). For the material behaviour indicated in Fig. 2, and neglecting the second order effect of the opening displacement of the actual crack tip, the rotational angle is given in differential form by

$$d\theta = -\mathrm{CTOA}/zb \tag{11}$$

As shown in Refs 10 and 13, the distance zb of the rotational center from the actual crack-tip is approximately

$$zb \cong c_2 b/2m \cong b/2 \tag{12}$$

By using eqns (10) and (12), Eqn (8) yields

$$U_n = c_1 c_2 \varepsilon_f \sigma_f t b_0 \rho/2 \tag{13}$$

and by eqns (9)–(12), one obtains from eqn (9)

$$U_{te} = -c_2 \sigma_f \frac{\mathrm{CTOA}}{2} mt \int_{b_0}^{0} b \, db \tag{14}$$

which gives, by integration,

$$U_{te} = c_2 \sigma_f mt \,\mathrm{CTOA}\, b_0^2/4 \tag{15}$$

With eqns (6), (7), (13) and (15) the CVN-upper-shelf energy becomes

$$A_{vus} = U_f = J_c b_0 t/2 + c_1 c_2 \varepsilon_f \sigma_f b_0 \rho t/2 + c_2 \sigma_f m t \,\mathrm{CTOA}\, b_0^2/4 \quad (16)$$

Before discussion of this result, we consider the special case where δ is not increasing with increasing crack-length as shown in Fig. 2, but remains constant at $\delta(\Delta a) = \delta_c$. Physically, this is approximately true for pure plane stress conditions, i.e. for cracks in very thin sheets. In this case, the rotational angle is related to crack-depth by

$$\theta = \delta_c/(zb) \cong 2\delta_c/b \quad (17)$$

Inserting eqns (10), (12) and (17) in eqn (9) and using eqn (4) one obtains

$$U_{te} = J_c b_0 t c_2/2m \quad (18)$$

Thus, for this special type of materials, the CVN-upper-shelf-energy is

$$A_{vus} = U_f = J_c b_0 t\left(1 + \frac{c_2}{2m}\right) + c_1 c_2 \varepsilon_f \sigma_f b_0 t \rho/2 \quad (19)$$

5 DISCUSSION

Consider the relation between the CVN upper shelf energy and J_c first for the general case of tearing crack-propagation according to Fig. 2 eqn (16). The first term in eqn (16) obviously is linear in J_c. The second can be written as

$$U_n \cong c_1 c_2 J_c b_0 \rho \varepsilon_f/(2m\delta_c) \quad (20)$$

For $\delta_c > \rho$, (i.e. for relatively tough materials) and $\varepsilon_f \leq 1$, the second term in eqn (16) is significantly smaller than both the others. Furthermore, ε_f and δ_c both depend in about the same way on toughness. Thus this term will not disturb the linearity between A_{vus} and J_c very much. the third term of eqn (16) is linear in CTOA. This term can be much larger than both the others. Thus, a linear relationship between CVN and J_c requires a linear relationship between J and CTOA. In general, this is certainly not true. This probably explains why there is no general correlation formula between A_{vus} and J_c. However, within certain families of metals—whatever this means (e.g. steels with the same chemical composition, but different heat treatments)—J and CTOA are related to each other, since there are some common features in the micro-mechanisms producing crack-initiation and tearing crack-growth.

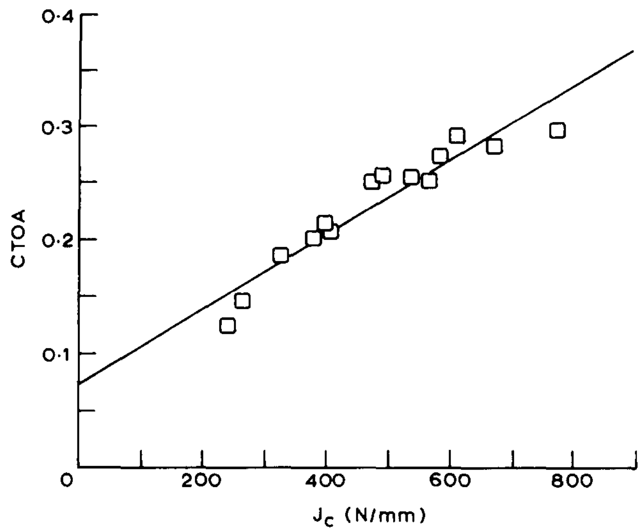

Fig. 5. CTOA versus J_c for an austenitic steel with different heat-treatment.

As shown in Fig. 5 by the example of a 'family' of the same austenitic steels with different heat treatment,[14] this relation can be more or less linear, explaining the linear relation between A_{vus} and J_c (Fig. 6).

According to the discussion above, an even better correlation should exist for the special case underlying eqn (19), since the term containing CTOA is missing and the first, linear term is larger. As stated above,

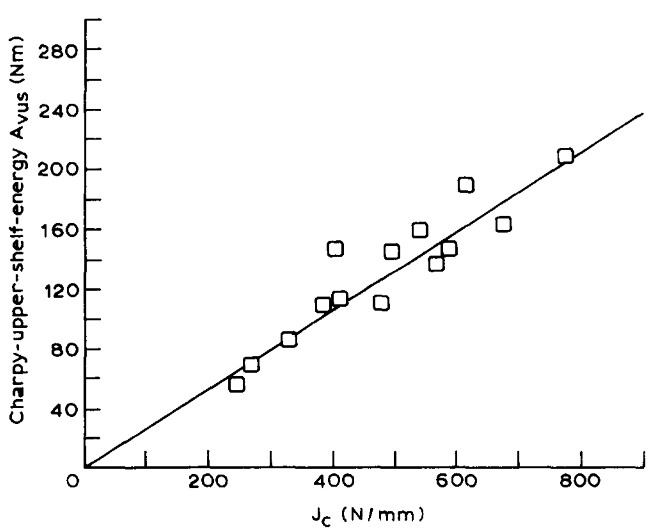

Fig. 6. J_c versus A_{vus} for the material of Fig. 5.

this type of crack-propagation may be ascribed to plane stress condition at the crack-tip, where the fracture process is dominated by local necking, e.g. cracks in thin sheets. A similar behaviour is likely to be present in the case of layered or fibrous material. Thus, this may be the reason why for wrought iron, which consists of numerous microscopic sheet-like layers, the relation between J_c and A_{vus} is significantly different from ordinary mild steel.[7,8]

A simple, approximate method for evaluating J_c from instrumented Charpy tests is suggested in Ref. 10. This method can be used for estimating J_c in those cases, where correlation-formulas can not be applied or where the proportionality-factor q (see eqn (1)) ought to be determined. Briefly, this procedure goes as follows. The amount of stable crack-growth up to maximum load, Δa_m, can be estimated by the formula $\Delta a_m = nb_0/2 + n$, where n denotes the hardening-exponent. The corresponding J, J_m, can be calculated analogously to eqn (7) from the consumed energy at maximum load. From this one can calculate the corresponding δ by means of eqn (4). CTOA is estimated from U_{te} by eqn (15). Therewith, the corresponding δ–R curve (see Fig. 2) is determined and evaluation of δ_c is possible by intersecting the δ–R curve with the initial blunting line (given by $\delta = 2\Delta a$), from which J_c follows immediately by use of eqn (4).

6 CONCLUSIONS

The above theoretical relations confirm that a general, unique correlation formula for estimating J_c or K_{Ic} from CVN-fracture energy does not exist. However, within a family or group of similar materials there seems to be an approximately linear relation should be determined for each family separately. For example, knowing the A_{vus} of two similar steels and J_c of one of them, it is justified to scale J_c by the quotient of the corresponding A_{vus} to estimate the missing J_c.

These correlations only hold in the upper-shelf region. In the transition and the lower-shelf region satisfying relations can not be expected. In these regions fracture mechanics tests are necessary.

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