THE RELATIONSHIP BETWEEN COD AND THE LOAD-LINE DISPLACEMENT IN CT-SPECIMENS

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Dawes' formula to calculate COD from the clip-gauge displacement is not correct from the physical point of view. This is proved theoretically and experimentally. A physically more reasonable proposal of a calculation formula is suggested.

INTRODUCTION

It is a main disadvantage of the crack-opening-displacement (COD) concept that it is difficult to determine COD experimentally. Many attempts have been made to calculate COD from the load vs. clip-gauge displacement curve. The British Standard for COD testing BS 5762 (1) specifies that COD should be calculated using the relationship

$$\delta = \delta_e + \delta_p = \frac{K^2 (1 - \nu^2)}{2 \sigma_y E} + \frac{r_p (w - a)}{r_p (w - a) + a + z} \cdot v_p \qquad (1)$$

with $r_p = 0.4$.

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This formula was developed by Dawes ((2), cited in (3)) for 3-point bend specimens. The first part of Eq. 1, δ_e, is called the elastic component of COD* and depends on the value of the stress intensity, K.

The plastic component of COD*, δ_p, is estimated from the plastic part of the clip-gauge displacement, v_p, assuming that the two specimen halves rotate about a hinge during the opening. The calculation is complicated because the position of the hinge (at a distance of $r_p(w-a)$ from the crack tip) depends not only on the specimen geometry but also on the degree of plasticity of the specimen, i.e. the plastic rotational factor, r_p, increases during loading. Dawes suggested an (average) value of $r_p = 0.4$.

Eq. 1 and some other similar formulae have been applied for compact-tension (CT) specimens, too, although up to now they have not been validated for this geometry. In the current work a first step should be made to do this.

EXPERIMENTAL

The material investigated was a structural steel, tempered for 4 hours at 700°C. Two series of CT 1-specimens were machined, with a thickness of either B = 25 mm (a/w = 0.55) or B = 1.5 mm (a/w = 0.71).

The microstructure had small carbide particles embedded in a ferrite matrix and a great number of MnS-inclusions directed parallel to the crack front (S-T crack-plane orientation). The chemical composition and the conventional mechanical properties at room temperature (RT) are given in Tab. 1. The specimens were precracked in fatigue. From each of the series five specimens were loaded to different amounts at RT and sub-

TABLE 1 - Chemical Composition and Mechanical Properties

C	Mn	Si	P	S	Ni	Cr	Mo	Cu	As
0.17	0.54	0.01	0.019	0.018	0.04	0.01	0.01	0.01	0.002

Yield strength	Tensile strength	Youngs modulus	Work-hardening coefficient
σ_y = 298 MNm^{-2}	σ_{UTS} = 426 MNm^{-2}	E = 200 GNm^{-2}	n = 0.20

*As discussed below this is a somewhat misleading nomenclature.

sequently broken in liquid nitrogen (without prior unloading). The failure mechanism was ductile tearing at RT and transgranular cleavage at -196°C. This change of the failure mode allowed an accurate determination of the amount of crack tip blunting.

COD was determined near the midsection of each specimen using the method of stereophotogrammetry with the scanning-electron microscope, which has been proved to be a very accurate method to measure COD (Kolednik and Stüwe (4), Broek (5)).

The method, described elsewhere (Kolednik (6)), was already applied successfully in investigations where the relationship between the J-integral and COD was studied (Kolednik and Stüwe (7,8)).

As shown in (4) it is essential to analyze the same regions on both specimen halves. So one gets sections perpendicular to the crack front, as illustrated by Fig. 1.

RESULTS

Tab. 2 summarizes the results of the stereoscopic measurements and the related data from the load vs. load-line displacement curves.

In Fig. 2 the measured COD-values are compared with the calculated ones which are also listed in Tab. 2. Generally, Eq. 1 overestimates COD, for small COD-values almost by 100 percent.

On the other hand, a good correlation can be found between COD and the plastic component of the load-line

TABLE 2 - Experimental Results and Calculated COD-Values

SPEC	B (mm)	a (mm)	v (mm)	v_p (mm)	K ($Nmm^{-3/2}$)	COD (μm)	δ (μm)	δ_e (μm)	δ_p (μm)
1	25	27.05	0.235	0.045	1567	15	29	19	10
2	25	27.56	0.295	0.07	1790	27	40	25	15
3	25	27.33	0.355	0.115	1844	38	52	26	26
4	25	27.65	0.40	0.145	1952	57	61	29	32
5	25	26.67	0.475	0.210	2122	71	86	34	52
6	1.5	35.51	0.32	0.10	1327	18	27	13	14
7	1.5	35.07	0.415	0.24	1258	29	47	12	35
8	1.5	35.86	0.505	0.285	1264	43	51	12	39
9	1.5	35.55	0.675	0.445	1366	58	76	14	62
10	1.5	35.47	0.89	0.64	1381	86	105	15	90

displacement, v_p (Fig. 3). So one may have doubts about the validity of Eq. 1, at least for CT-specimens.

DISCUSSION

Sometimes there seems to be confusion about the meaning of δ_e in Dawes' formula. Therefore, it should be emphasized here that δ_e is the plastic displacement of the crack tip when linear elastic fracture mechanics (LEFM) would be applicable. If a specimen were cut into two parts (e.g. by fracturing in liquid nitrogen) without prior unloading, COD would be diminished by a very little extent of about $\varepsilon_y \cdot$COD (ε_y = yield strain). When the specimen is unloaded to zero the blunted crack tip will be re-deformed plastically by a small amount. According to a model of Rice (9) that amount should be equal to $0.5 \cdot \delta_e$.

Now we assume a valid K_{IC}-test. LEFM is applicable, therefore one can estimate COD using the equation

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_y E} \tag{2}$$

Any plastic deformation at the crack tip will produce a plastic component of the load-line displacement, v_p, too. So, if we knew the right value of the rotational factor, r_p, we could also estimate COD applying the relationship

$$\delta = \frac{r_p(w-a)}{r_p(w-a)+a} v_p \tag{3}$$

One can estimate COD using either Eq. 2 or Eq. 3. In Eq. 1 Dawes makes the mistake to add these two δ-values. This is the reason why Eq. 1 yields too high δ-values, especially in cases when Eq. 2 still produces reasonable results, i.e. for small v_p-values (see Fig. 2).

From these considerations we can deduce that a physically correct relationship between COD and the clip-gauge displacement must consist of the second part of Eq. 1 only. This must be true irrespective of specimen geometry.

Looking at Tab. 2 you see that for the thinner specimens the calculated δ_p-values come very close to the measured CODs. So one may conclude that the assumed rotational factor $r_p = 0.4$ is correct for this specimen geometry. For the thicker specimens the calculated δ_p-

values are smaller than the measured CODs, therefore r_p must be higher than 0.4 in that case.

There is an experimental explanation for the fact that r_p must be higher in the thicker specimens: From Spec. 3 and Spec. 5 (B = 25 mm) the COD-values at the outside of the specimens were measured, too (Kutlesa (12)). In both cases the outside-CODs have only 65% the size of the centre-values.

For a thick specimen (small outside regions and large centre region) the centre-COD is relevant for the opening of the specimen and the size of the rotational factor will be underestimated, if the outside-COD is used to determine r_p. With a decreasing specimen thickness the outside-COD becomes more and more important and r_p decreases.

The slopes of the curves of Fig. 3 depend on the size of r_p and on a/w. As r_p increases with the degree of plasticity of the specimen one would expect a less steep COD-v_p-curve at the origin. With further loading the slope should increase. After reaching the plastic limit load r_p and the slope of the curve should remain constant.

The plastic limit load, F_{GY}, was calculated following lower bound analysis* of Merkle and Corten (10)

$$F_{GY} = \sigma_y \, B(w - a)\, \gamma \qquad (4a)$$

with

$$\gamma = \frac{\sqrt{2}\,\sqrt{1 + (a/w)^2} - (1 + a/w)}{1 - a/w} \qquad (4b)$$

Because of the low yield strength of our material the plastic limit loads are small: F_{GY} lies slightly above the maximum load of Spec. 2 for the thicker specimens and below the maximum load of Spec. 6 for the thinner ones. Therefore, the plastic rotational factor very soon reaches its maximum value and no non-linearity of the COD-v_p-relationship can be observed in Fig. 3.

*ignoring the stress triaxially caused by the crack tip

An experimental verification of a calculation formula (as Eq. 1) can be only as good as the method of COD-measurement. Generally, these formulae have not been proved satisfactorily, because there exist very few investigations where COD (in the midsection of the specimens!) was measured directly.

In (11) Robinson and Tetelman studied the relationship between COD (measured with the infiltration method) and the off-load angle of bend, testing A 533 B steel-Charpy specimens (see Fig. 4).

For small values the off-load angle of bend is proportional to the plastic component of a clip-gauge displacement. So, again, a linear relationship between COD and v_p is observed.

CONCLUSIONS

1. Dawes' formula is not correct from the physical point of view, neither for CT-specimens nor for any other specimen geometry.
2. Like Eq. 3 a correct calculation formula should relate COD with the plastic component of the clip-gauge displacement, v_p, only.
3. After general yield the plastic rotational factor remains constant and a linear relationship between COD and v_p appears.
4. For low-strength materials this line will start from the origin.

SYMBOLS USED

a = crack length (m)
B = specimen thickness (m)
COD = real value of the crack-opening displacement (m)
E = Youngs modulus (N/m^2)
F_{GY} = plastic limit load (N)
K = stress intensity ($N/m^{3/2}$)
r_p = plastic rotational factor (1)
v = clip-gauge displacement (m)
v_p = plastic component of v (m)
w = specimen width (m)
z = clip-gauge abutment height (m)
γ = constant defining the position of the stress-reversal point on the ligament (m)

δ = calculated value of COD (m)
δ_e = "elastic" component of δ (m)
δ_p = "plastic" component of δ (m)
ε_y = yield strain (1)
ν = Poisson's ratio (1)
σ_y = yield strength (N/m^2)

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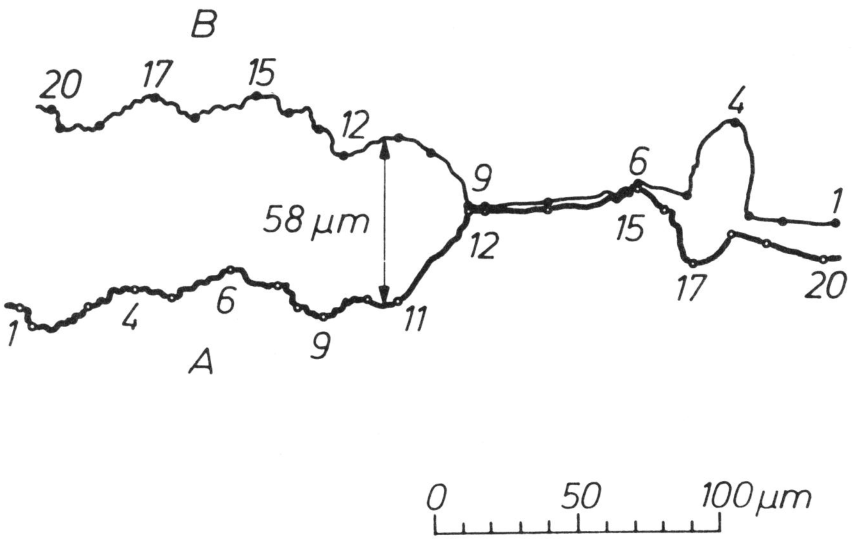

Figure 1 Result of the stereoscopic measurement of Spec. 4, from (7)

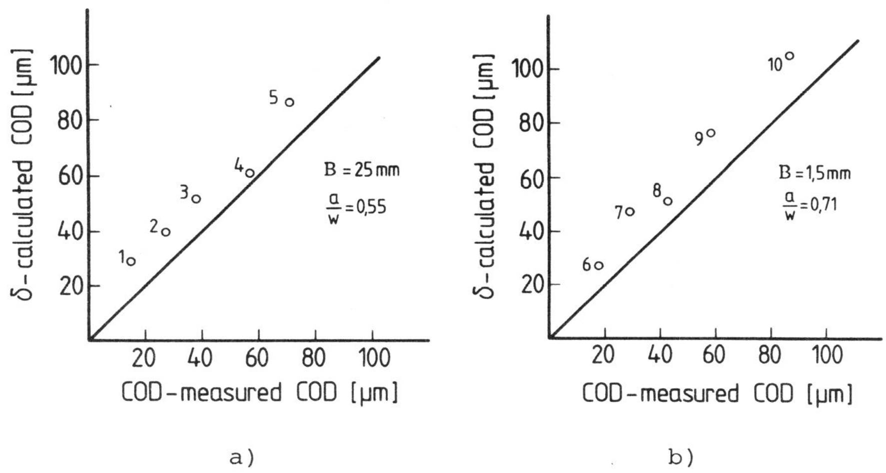

Figure 2 Relationship between measured and calculated COD, a) B = 25 mm, b) B = 1.5 mm

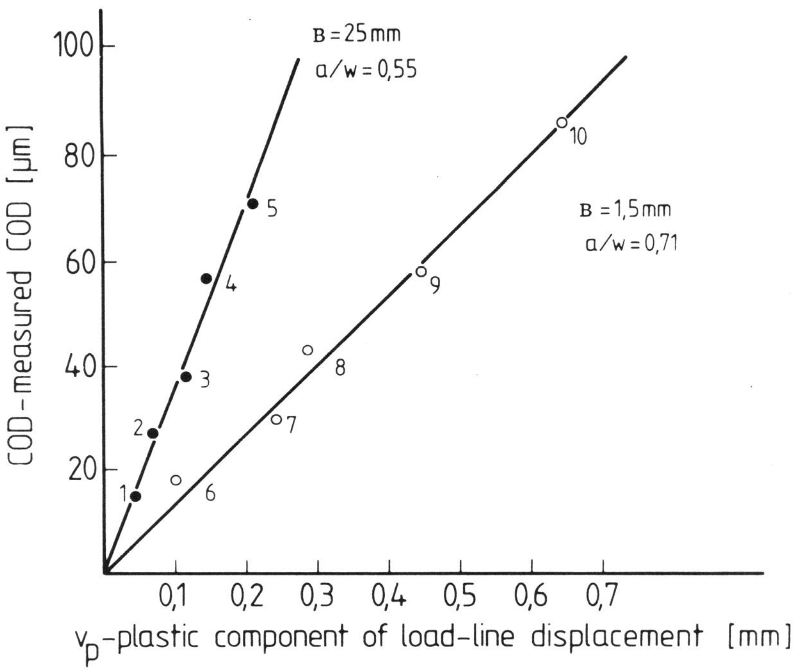

Figure 3 Relationship between COD and the plastic component of load-line displacement

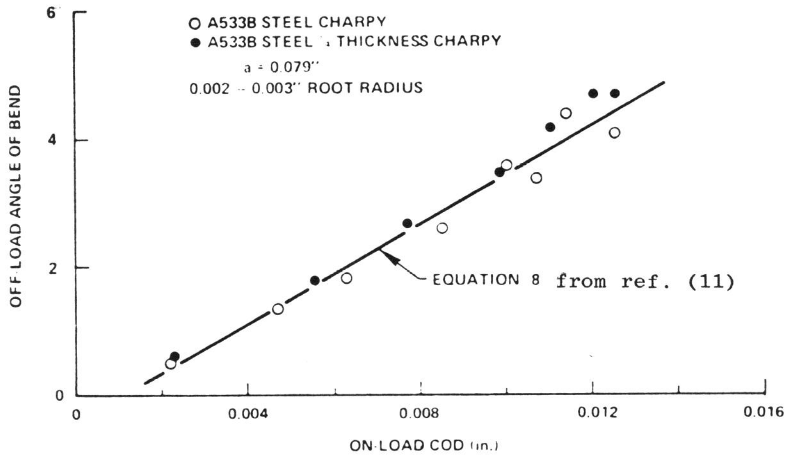

Figure 4 On-load COD versus off-load angle of bend for Charpy specimens, from (11)