THE EXPERIMENTAL INVESTIGATION ON DEFORMATION AND OPENING DISPLACEMENT OF CRACK TIP[1]

XUEWEI SUN, WEIDI CAO and XIAOPING LU
Tsinghua University, Beijing 100084, P.R. China

ABSTRACT

By indirect method (method of extrapolation from clip gauges) and direct method (method of hardening silicone rubber replication, method of matching fracture surface and method of section), the crack-tip opening displacement (CTOD) of four classes of steel with different yielding strength and hardening ability are measured to investigate the changes of CTOD with load and materials properties. In general the values of CTOD obtained from indirect method are bigger than those obtained from direct method. Their differences increase with the decrease of CTOD and the increase of yielding strength, as is the result of inplastical hinge deformation mechanism around the crack tip. According to the results of experiments, the deformation mechanisms around the crack tip are discussed. Based on the suggested deformation mechanism in this paper, some appropriate proposals about on the methods of measuring CTOD are given also.

KEYWORDS

Crack-Tip Openign Displacement (CTOD), deformation mechanism, experimental measurement, inplastical hinge deformation mechanism

INTRODUCTION

Crack-tip opening displacement (CTOD) has been accepted extensively as a criterion of fracture and applied successfully to the engineering against failure design. The critical value of CTOD (or δ_c , as an important parameter of material against rupture, has been measured for many of materials. Up to now, the standard method of measuring (CTOD) is the indirect method of extraplation from clip gauges [1-3]. Some other methods, such as the replication method of hardening silicone rubber [4-7] and the analysis method of matching fracture surface [8-11] were

---

① Sponsored by the National Natural Science Foundation of China and by FO Yingdong's Education Foundation

suggested also. But there are some drawbacks in all these methods. Some experiments show that CTOD calculated from clip gauges using a constant rotational factor r has considerable discrepancies with the result of direct method of silicone rubber replication [4]. A modified rotational factor was suggested based on the experimental results. But the physical meaning of the modified method isn't clear. Due to lack of understanding of the deformation behaviors around the crack tip, the exact position, at which the true opening displacement as the original crack tip is obtained, can't be determined in the method of silicone rubber. At present, some different standards are usually adopted according to some simplified deformation models. For example, CTOD can be defined by the relative opening displacement at the knee points from the linear part to the curved part of the crack profile or at the positions of the crack surface, where the two lines, which are drawn from the apex of the crack at an angle of 45 ° or 30 ° , intersect with the crack profile [13,6]. By these methods, an identical results is difficult to be obtained. During loading, the crack tip is blunting and a characteristic region termed stretched zone (SZ) is developed. The depth of SZ (2SZD) reflects the level of the opening displacement at the crack tip. CTOD can also be estimated by measuring 2SZD from the fracture surface. But our investigation [11] showed that 2SZD is rather smaller than the result obtained from clip gauges. This difference can't be explained only by the fact that the elastic opening displacements are not included by 2SZD. Therefore more basic research work is needed to establish a correct method of measuring CTOD.

The key of the above problems is lack of understanding the deformation law around the crack tip. This law, which is related with not only the establishment of the method of measuring CTOD but also a series of problems of fatigue fracture, is an important problems to study. In the present paper, the deformation behaviors at the crack tip for several classes of steel with different toughness and hardening ability are investigated. CTOD are measured by several methods in order to abtain the influences of deformation mechanisms around the crack tip on the measured results of CTOD. Moreover, some preliminary discussion on the reasonable method of measuring CTOD is made.

EXPERIMENTAL PROCEDURE

Four classes of materials with different yielding strengths from 400MPa to 800MPa and hardening abilities are used to investigate the influences of these factors on the deformation around the crack tip. The chemical compositions and mechanical properties of materials are given in Table 1 and 2, respectively.

Table 1. Material compositions (wt%)

Material	C	Si	Mn	Ni	Cr	Mo	N	V	Nb
15MnVN	0.12	0.30	1.45	—	—	—	0.016	0.08	—
18MnNiMoNb	0.20	0.30	1.45	0.80	—	0.55	—	—	0.04
9Ni	0.12	0.20	0.75	9.10	—	—	—	—	—
40CrNiMoA	0.40	0.30	0.71	1.85	0.80	0.25	—	—	—

Table 2. Mechanical properties

Material	σ_s(MPa)	σ_b(MPa)	δ(%)	ψ(%)	n	δ_c(mm)
15MnVN	417	562	30.3	65.1	0.124	0.086
18MnNiMoNb	606	732	20.1	71.6	0.035	0.160
9Ni	705	805	28.1	70.5	0.121	0.080
40CrNiMoA	801	898	9.75	62.3	0.106	0.071

In order to investigate the developing process of CTOD during loading, one group of specimen for every class of material is prepared and loaded to different prescribed levels of CTOD. From the load P versus dispacement of loading point △ curves, the J-integral corresponding to the prescribed loading points can be calculated by following formula [14]

$$J = (1 - \nu^2)(PY / B)^2 / EW + 2U_p / B(W - a) \qquad (1)$$

where E is Young's modulus, ν is Poisson's ratio, B, W and a are the thickness, width of the specimen and the length of crack, respectively, Y is a compliance factor, and U_p is the plastic deformation work.

Further, the four following methods are used to measure CTOD of the prescribed loading points.

(a) According to the national standard of China GB2358−80 i.e, "Methods of measuring CTOD", CTOD or δ of the prescribed loading point can be obtained by indirect calculation from the opening displacement at the crack tip using the following relationship

$$\delta = (1 - \nu^2)(PY / B)^2 / 2EW\sigma_s + V_p / (1 + (a + z) / r_p(W - a)) \qquad (2)$$

where V_p is the plastic part of crack mouth displacement V, r_p is a plastic rotational factor which is taken to be equal to 0.45 according to the national standard.

(b) Under sustained load at the prescribed loading points, suck liquid silicone rubber into the crack. After the silicone rubber is hardened, we can get the silicone rubber casting under a higher load level, get the casting and suck liquid silicone rubber into the crack again and get another casting (as is called the continuous replication method), Or we can produce a secondary crack by a fatigue testing machine after unloading, whose maximum load and average load are about 80% and 60% of the load at the prescribed loading point, respectively. After the secondary crack reaches the length 2mm, the specimen is compressed to fracture and the casting is got. (as is called the replication method of prescribed point). The hardened silicone rubber casting is sectioned from the width center and sprayed Carbon. Then the crack profiles are photoed from the scanning electron microscope. CTOD is measured from the photography according to the following standards, as shown in Fig.1.

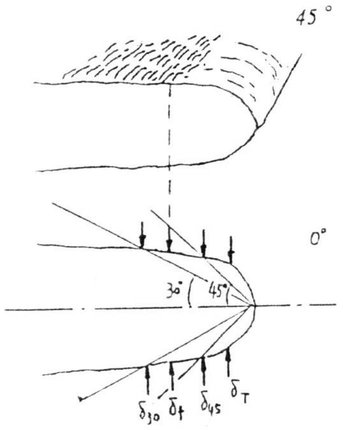


Fig.1 Diagrammatic sketch of some methods of determining CTOD

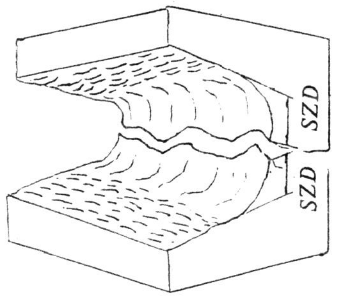


Fig.2 Schematic drawing of the method of determining CTOD by matching fracture surface

1) CTOD at the knee point from the linear part to the curved part of the crack profile or δ_T;

2) CTOD at an angle of 45 ° , or δ_{45};
3) CTOD at an angle of 30 ° , or δ_{30};
4) CTOD at the intersection of SZ and the fatigue zone, or δ_f.

Under the situation of better replication, we find that the profiles of the fatigued fracture surface and SZ can be replicated by the flank of the silicone rubber casting. So from the photography of the replication, the intersection line of SZ and the fatigued zones and its intersection point with the out profiles can be determined. The distance between the two crack flanks at the point is defined as δ_f. Because the boundary of SZ is approximately corresponding to the original crack tip position, the clasest one to the value of CTOD at the crack tip.

(c) Observing the fracture surface of the replicated specimen under scanning electron microscope, SZ can be found clearly at the intersection between the first and secondary fatigue cracks. The stretched zone width (SZW) and depth (SZD) can be measured from different photographies. After the exact matching point on the two half of the fracture surface is determine from the photography of SZD, the avergage of 2(SZD) is obtained by taking the average of SZD of every matching points, which is defined as CTOD obtained by the method of fractgraphy and remarked as δ_{SZ} or 2(SZD), as shown in Fig.2.

(d) The specimen loaded to the prescribed point is unloaded, sectioned from the width center, plated Nickel in order that the plating shows the exact profile of the opening crack, and made into a specimen of metallography. Then the average value of CTOD of five different sections is measured by the method of optical metallography, which is marked as δ_{sect}. When CTOD is small, the two crack shores near the tip aren't straight due to the influence of closure effect and the deformation features of crack itself. Then the maximum distance between the two shores at the crack tip is defined as δ_{sect}.

EXPERIMENTAL RESULTS

1. Relationship between J and δ.

Fig.3 shows the relation between J-integral and δ (or CTOD). It can be expressed as

$$J = 1.902\sigma_s\delta \qquad (3)$$

which is consistent with result of fracture mechanical properties has no evident influence on the relation.

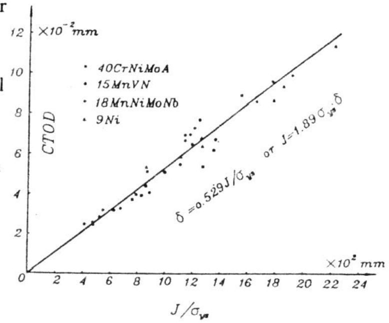


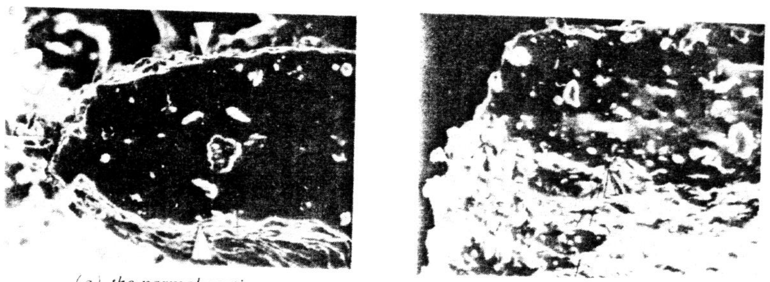
Fig.3 Relation between CTOD measured by clip gauges and J/σ_{ys}

2. Result from method of silicone rubber

The shape features of silicone rubber castings is shown by Fig.4, in which Fig.4 (a) gives and shape of normal section. It should be pointed that sometimes the knee point of the outer profile of open crack is too underminable to give the value of δ_T exactly. Moreover, depending on the blunted crack tip shape, the lines drawn from the crack apex at an angle of 45 ° can't even intersect with the horizontal part of the crack sometimes, and the result obtained is smaller even than δ_T. Fig.4(b) shows the profiles of the replica with an angle of 45 ° with the electron beam. As shown in this Figure, the intersection of SZ and fatigue zone can be determined approximately.

The comparison of δ_{30}, δ_{45} and δ is shown in Fig.5 (a,b). The comparison of δ_f and δ_T is similar. From these relations, the following conclusions can be obtained:

(1) In general, $\delta_{30} > \delta_f > \delta_{45} > \delta_T$, and δ_{30} is the closest one to the result from clip gauges. But δ_{30} still smaller than the result from clip gauges, especially for steel with high strength.As discussed above, considered from the deformation mechanism of crack, δ_f should be near to CTOD of the original crack tip position. So δ obtained from clip gauges overestimated the true value of CTOD.



(a) the normal section (b) the profiles of the replica with an angle of 45 °

Fig.4 The shape features of silicone rubber castings

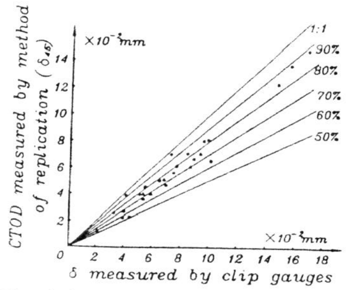


Fig.5(a) Relation between δ measured by clip gauges and CTOD (δ_{45}) measured by method of replication

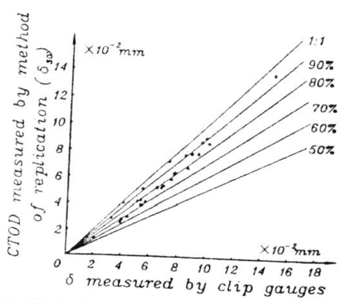


Fig.5(b) Relation between δ measured by clip gauges and CTOD (δ_{30}) measured by method of replication

(2) The relation of CTOD from the silicone rubber replication δ is influenced by the level of CTOD and the mechanical properties of materials. Their difference increases with the decrease of CTOD, as is similar to the result of Robinston [4] , and with the raise of yielding strength. For example, neglecting the change of the difference between δ_{30} and δ with the level of CTOD, the following value of δ_{30} can be obtained by method of least squares.

$$\begin{aligned} &\delta_{30}=0.8867\delta,\ \text{for 15MnVN} && \delta_{30}=1.0350\delta,\ \text{for 18MnNiMoNb} \\ &\delta_{30}=0.7845\delta,\ \text{for 9Ni} && \delta_{30}=0.7830\delta,\ \text{for 40CrNiMoA} \end{aligned} \qquad (4)$$

Neglecting the influences of CTOD and mechanical properties of materialsm, the following relations between CTOD and δ and be obtained by the replication method.

$$\begin{aligned} &\delta_{45}=-0.0072+0.87\delta && R=0.9676 \\ &\delta_{30}=-0.0149+1.07\delta && R=0.9772 \\ &\delta_{4}=-0.0152+1.07\delta && R=0.9839 \end{aligned} \qquad (5)$$

3. Result from fractgraphy

The shapes of SZW and the matching SZD are shown in Fig.6. The relations between SZW or 2SZD and δ or obtained here are similar to those in [11].

a) There isn't a unique correlation between SZW and δ (or J/σ_s). So SZW isn't a parameter equivalent to δ. But there is a better correlation between SZW and J / E, which can be expressed as

$$SZW = 0.0027+65.8J/E, \qquad R=0.964$$

or can be expressed approximately as

$$SZW = 74J / E \qquad (6)$$

This relation is more or less alike to the result of
Kobayashi in [15] and the result in [11], but its proportional coefficient is smaller. Fig.8 shows also that the
properties of materials such as yielding stength still have
a little influence on this relation, as may be the reason of
scattering of data.

b) There is a better correlation between 2(SZD) and
J / σ_s. So 2(SZD) is a parameter more or less equivalent
to δ. The relation of 2(SZD) and J / σ_s can be given as

$$2(SZD) = 0.3112J / \sigma_s \qquad (7)$$

(7) has the same form as (3). But if (7) is re-expressed as
$J = m\sigma_s\delta$, then the value of m is much bigger than that
from clip gauges.

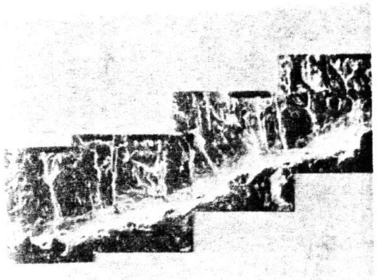


Fig.6 The shapes of SZW

This point can be shown more clearly by the relation between 2(SZD) and δ, which can be expressed as

$$2(SZD) = -0.0066+0.738\delta, \qquad R = 0.947$$

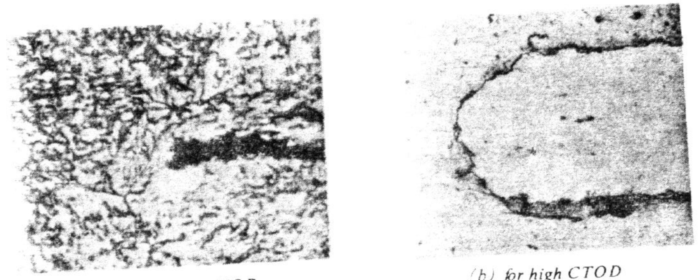
$$\text{or} \quad 2(SZD) = 0.74\delta \qquad (8)$$

This formula is similar to our result in [11] 2(SZD) = 0.55δ. δ in [11] was calculated from the for-
mula of Dawes in [2] where r was equal to 0.40, so its proportional coefficient is smaller.
c) The difference between 2(SZD) and δ is influenced by the properties of materials and the level of
CTOD. This difference is bigger when the yielding strength is higher and CTOD is lower. For ex-
ample, neglecting the influence of CTOD, the following relation can be obtained for four classes of
materials.

$$2(SZD) = 0.628\delta, \text{ for 15MnVN} \qquad 2(SZD) = 0.689\delta, \text{ for 18MnNiMoNb}$$
$$2(SZD) = 0.554\delta, \text{ for 9Ni} \qquad 2(SZD) = 0.571\delta, \text{ for 40CrNiMoA} \qquad (9)$$

4. Results from the section method

Fig.7 shows the profiles of the Nickle-plated section of the unload crack. It is noticed that the
blunted crack tip shapes change evidently from the crack with two sharp angles for low CTOD
Fig.7 (a) to the crack with rather ideal half circle for high CTOD (Fig.7 (b)). Fig.8 gives the com-
pletely same as the result from fractgraphy. In fact, both the method of matching fracture surface
and the section method given the values of unloaded CTOD, between which there is almost a cor-
relation.



(a) for low CTOD (b) for high CTOD

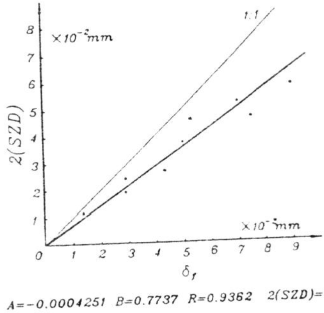
Fig.7 The profiles of the nickle-plated section of the unload crack

CONCLUSIONS

(1) It is shown by investigation on the different methods of measuring CTOD that CTOD from the current standard indirect method is bigger than that at the original crack tip poistion. Their difference incrases with decreasing CTOD and raising yielding strength of materials.

(2) This phenomenon is related with the two combined deformation mechanism around the crack tip, i.e, the plastical hinge mechanism and the inplastical hinge mechanism.

(3) For the current indirect method of measuring CTOD, it is reasonable that the rotational factor r is chosen to be 0.40 for the case of CTOD > 0.1mm, and to be a approrpariat value from Fig.8 for the case of small CTOD.



A=-0.0004251 B=0.7737 R=0.9362 2(SZD)=0.765·δ_f

Fig.8 Relation between δ_f and 2(SZD)

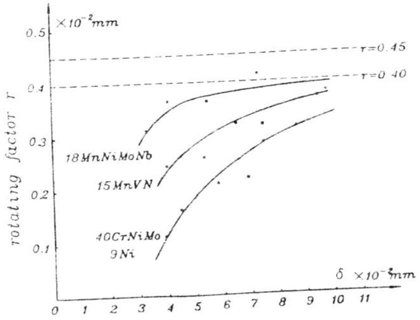


Fig.9 Relation between rotationg factor r and δ

(4) Measured at the intersection of fatigue zone and stretch zone over crack flank of silicone rubber replica, δ_f reflects the rather exactly opening displacement at the original crack tip position, and can be regarded as a reference of CTOD measured by the method of silicone rubber replication.

(5) The unloaded CTOD or 2(SZD) obtained by the method of fracture surface is smaller than the true CTOD. The value of loading CTOD can be estimated by the relation $\delta = 1.25(2SZD)$.

REFERENCES

[1] Method for Crack Opening Displacement (COD) Testing, Draft for Development, DD19: 1972, British Standard Institution, London (1972)
[2] M.G.Dawes: Elastis-Plastic Fracture, ASTM STP668 (1979), PP.307-333
[3] BS5762: 1979
[4] J.N.Robinson & A.S.Tstelman: Fracture Toughness and Slow-stable Cracking, ASTM STP559 (1974), PP.139-146
[5] B.A.Fields and K.J.Miller: A Study on COD and Crack Intiation by a Replication Technique, E.F.M. Vol9, 1977, PP.137-146
[6] H.Knauf & H.Riedel: ICF 5 Vol.P.2547 (1981)
[7] S.Xuewei et al, Engineering Transactions, 32, 1, PP.123-129, 1984
[8] A.Otsuka: In "Fracture Mechanics and Technology", 1977, Vol.2, P.539
[9] C.K.Clarke: ICF 4 Vol.3a P.321, 1977