Photos of deform^n in 2-notches
Results on 3 Cr-Mo V.

PAPER 1 (SESSION I)

A study of the C.O.D. concept for brittle fracture initiation

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Summary

The C.O.D. (crack opening displacement) concept is developed as a criterion for the initiation of brittle fracture. The validity of this concept was checked by tensile, bend and charpy type impact bend tests using mild steel plate. Critical C.O.D. values were directly measured by taking micro-photographs. A description of the test equipment is given, and the results of the tests analysed and discussed. It is concluded that the 'double notch' test is a useful method for measuring the critical C.O.D., but the 'overall displacement' method, is at present unsatisfactory.

Introduction

As is well known, two typical alternatives have been available for a practical approach to the problem of the onset of the brittle fracture propagation. One is the concept of 'fracture stress curve' and the other is the energy criterion or *K*c concept. In the former, case the difficulty of obtaining an accurate measurement of stress and strain values associated with the macroscopic plastic deformation at a crack tip prevents its application for practical engineering design.

In the latter case, however, many experiments [1] have shown that the Griffith-Orowan type fracture theory, or fracture mechanics in a narrow sense, has a validity for the practical problems, as long as the plastic deformation at the crack tip is sufficiently small compared with crack length (small scale yielding). However, numerous service failures are believed to have occurred under conditions which do not satisfy the small scale yielding.

The C.O.D. (crack opening displacement) concept is noteworthy and promising as a new fracture criterion though it contains some unsolved problems. While the C.O.D. concept has received some criticism [2] from the viewpoint that it does not have any clear physical meaning, it remains significant enough to be subjected to further investigation as an engineering criterion [3].

In fact some additional physical conditions are necessary to prove that C.O.D. concept is to be a necessary and sufficient condition (or either of them) for fracture. But as long as the fracture is intrinsically related closely with plastic stress and strain concentration at the crack tip, the C.O.D. criterion appear very plausible since it seems to represent roughly the integrated value of plastic strain in the crack tip plastic zone.

A. A. Wells [4] was the first to appreciate the practical meaning of C.O.D. concept as a fracture criterion and a study was also carried out by Bilby *et al.* [5] from the mathematical point of view. However, a satisfactory experimental check on its validity has not been performed. Recently, Koshiga *et al.* [6] found an Arrhenius-type temperature dependence of critical C.O.D. by measuring over-all displacement of a deeply notched 30-50 mm wide and 3·2 mm thick tensile specimen. This shows an important track for an application of C.O.D. for practical engineering.

The authors, as part of a comprehensive engineering fracture criterion survey checked as the first step of the investigations, the validity of the C.O.D. criterion by tensile, bend and Charpy type impact bend tests using mild steel plate. Critical C.O.D. values were directly measured by taking microphotographs.

Direct measurement of C.O.D. with the use of doubly or parallel notched specimen

Any mechanical setup to pick up C.O.D. can hardly be attached to the conventional notched specimen considering that the specimens are to be fractured at various low temperatures by keeping them in a cooling bath and that the value of C.O.D. is the order of 1/10–1/100 mm for very brittle condition. A microphotograph technique was used in this investigation for the measurement of C.O.D. on a special specimen configuration, as in a conventional center or edge notched specimen, it is very difficult to keep the specimen at the load just below the unknown fracture load so as to measure critical C.O.D. by taking microphotographs.

As shown in Fig. 1, one or two pairs of symmetric parallel saw cut edge notches were machined in a specimen so that each of the notches might be subjected to the same stress and strain state. This will be called a ‘double notch test specimen’ hereafter. If all the notches in a double notch specimen undergo the same plastic opening displacement up to unstable fracture of the specimen which would surely be initiated from one of the notches, the critical C.O.D. would easily be obtained by measuring the C.O.D. of the unfractured notch. In its ideal sense, this might mean that the geometric configurations of specimens, especially those of each notch, should be absolutely identical. However there is a limitation in the accuracy of machining. In fact, the inevitable variation of notch root radius may be of an order comparable with that of the C.O.D. value itself, in a brittle condition. If the variation causes asymmetric deformation behavior, the test has no validity in the estimation of the critical C.O.D. values.

Effects of variation in notch root geometry on displacement behavior were checked using the tensile specimens illustrated in Fig. 1. An example of the test results shown in Fig. 2 and Table 1 indicates that comparably large variations such as 0·084 mm (about 42% of notch root radius) as a maximum does not cause any asymmetric displacement behavior for each notch, and fracture does not always start from the narrowest notch. Therefore, it can be concluded that the double notch test is valid to determine critical C.O.D. values.

Material and test procedure

The steel investigated was 20 mm thick structural mild steel plate and its particulars are given in Table 2. In addition to tensile tests, slow bend tests and Charpy type impact bend tests were performed in order to obtain the effects of temperature, loading system, plastic constraint and strain rate, on the critical C.O.D. The geometric configuration of each type of specimen is also shown in Fig. 1. All specimens were cut in longitudinal (or roll) direction except the Charpy type impact bend specimens which were cut in the transverse as well as in the longitudinal direction. The ratio of crack depth to specimen width was varied in order to observe the effect of plastic constraint on the critical C.O.D. value. The values of the ratio are 0·1 and 0·22 for the tensile specimen and 0·1, 0·17 and 0·2 for the slow bend specimen, the plate thickness being 20 mm. In the Charpy type specimen 2 mm and 3 mm long saw cut notches were used. Mirror surface finishing was made on the zone of the notch tip to permit accurate measurements. Microphotographs of 100 magnification of the notch roots were taken before and after the fracture test and three positions (about 0·1 mm apart) were selected for C.O.D. measurement along the notch in the vicinity of the notch tip as shown in Fig. 3. The average of the three values was taken as the crack width.

The tensile specimen was set up on the mechanically driven 100-tons testing machine as shown in Fig. 1. After keeping the specimen for ten minutes at the test temperature, tensile load was applied at 0·2 mm per minute cross-head speed. Three copper-constantan thermo-couples were attached on the crack lines as shown in Fig. 1.

After a specimen fractured, each unfractured notch width was measured using the same procedure as mentioned above and the difference from the initial notch width was taken as a critical C.O.D. value. In some of the tensile test specimens, short and small-scale brittle fractures were found at the notch root (they were arrested a centimeter or less from the notch) in the unfractured pair of notches. Even in such cases, good agreement was observed with the critical C.O.D. from notches from which no brittle crack was initiated. This suggests that each notch causes the same plastics deformation up to fracture and any unstable deformation of one particular notch cannot occur.

Test results

Measured values of critical C.O.D. were plotted for test temperature (shown in Figs. 5, 6 and 7) for each specimen.

These figures indicate as Koshiga *et al.* have pointed out previously [6], that the critical C.O.D. has the Arrhenius type temperature dependence. But the value of Φc at a certain temperature and the slope of the Arrhenius type temperature dependence curve seems to depend upon the conditions of the fracture test such as the loading system, the loading speed, the notch depth and so forth.

This factor must be included in any establishment of a practical test method for the evaluation of Φc if it is to be treated as a unique material parameter of crack initiation.

From Fig. 7 no significant difference in Φc can be observed between *L* (longitudinal) specimen and *C* (transverse) specimen. For reference the conventional Charpy transition curves of the steel tested are shown in Fig. 8 which shows that absorbed energy level of *C* specimen is significantly lower than that of *L* specimen, but almost no difference is seen in the fracture appearance transition. Thus Fig. 7 seems to provide an experimental verification in favor of the opinion that among the Charpy impact data the fracture appearance transition criterion is most important.

Discussion

The method of C.O.D. measurement

The methods of C.O.D. measurement so far available can be roughly classified into two except for the above-mentioned double notch test. In one the opening of the crack surfaces at the tip of the crack is detected by the rotation of a small and thin blade, which was tried by Burdekin *et al.* [7]. The other is based on the condition that with a proper choice of the relative notch length the plastic displacement is bounded at the environment of the crack tip (see Fig. 9) and thus the overall plastic deformation of the specimen will roughly represent the C.O.D. Koshiga *et al.* [6] adopted this method and measured the plastic deformation between specimen grips.

The former is of interest as a method of direct measurement of C.O.D., but it will hardly produce good accuracy for a very sharp notch. The

setting up of the C.O.D. meter will also be difficult under cooling conditions.

The latter is simple and effective for a commercial test. When large-scale yielding occurs, however, the overall displacement will contain a significant component due to the displacement other than C.O.D. So the conditions for the application of this method are very limited and a proper choice of specimen configuration is very difficult. As shown in Fig. 9, the plastic zone spreads even under smaller load and the sides of the notches are apt to rotate along slip lines. So the overall plastic displacement has these additional components, which depend on the notch depth as well as plastic characteristics of the material. So the method of indirect measurement of C.O.D. such as the overall displacement method should be adopted with much prudence, though it may generally give correct order of merit of the materials tested. To measure the absolute value of Φc is very important for the application of C.O.D. concept to structural design.

As shown in Fig. 10, significant difference between the directly measured C.O.D. and that estimated from overall plastic displacement is observed even at the early stage or small scale yielding. Since any accurate method to estimate these additional components in the overall displacement has not been available yet the method of direct measurement by means of microscope may be useful to obtain exact value of a critical C.O.D.

Effect of the distance between two parallel notches and the notch depth on C.O.D.

As shown in Fig. 1, the double notch test specimen has one or two pairs of rather closely located notches. The mutual distance of the notches would surely have some effect on the plastic constraint at the notch tip. Theoretical analysis of this effect seems difficult under the condition of crack tip opening after large scale or general yielding of strain hardening material, which is of the principal concern in the present investigation. So the effect on critical C.O.D. was investigated experimentally using the double notch tension test, in which notch depth was 20 mm and the distances between two parallel notches were 5, 8, 15, 30 and 50 mm. The results are shown in Fig. 11 as a function of the ratio of the distance between two notches to notch depth, *h/c*. This shows that if the value of *h/c* is smaller than 0·75, intensity of the effect on the critical C.O.D. increases. This corresponds to the transition from plane strain to plane stress fracture at the notch tip. In the specimen used, the values of *h/c* range from 0·75 to 3·75 that is the condition of plane strain fracture and the variation of the effect of the distance between two notches on the critical C.O.D. can be negligible.

The effect of strain rate

As shown in Figs. 5 to 7, the difference in log(Φc−1)/*T* curves due to the specimen geometry, the loading system and loading rate is considered to be attributed to the degree of constraint and strain rate in the notch tip material. Although the degree of the constraint is represented as a function of plastic stress and strain in a notch tip zone, the problem is reduced here for simplicity and is approached from the difference in the strain rate of notch tip material for each specimen, which is approximately calculated.

If we assume that the stress σ at the short distance r from the notch tip on the notch plane is elastic, σ is expressed as follows:

$$\sigma = \frac{K}{\sqrt{(2\pi r)}} \tag{1}$$

where K is the stress intensity factor.

Neuber [8] has obtained the following for the stress and strain concentration factor of longitudinal shear problem of non-linear material

$$\alpha_\epsilon \cdot \alpha_\sigma = \alpha_t^{\,2} \tag{2}$$

where α_ϵ is the strain concentration factor, α_σ is the stress concentration factor and α_t is the concentration factor for linearly elastic case.

Assuming the power law in stress-strain relations, (2) is reduced to

$$\alpha_\epsilon = \alpha_t^{\,2/(n+1)} \tag{3}$$

Designating nominal stress and strain by σ_n and ϵ_n respectively, the following results from (1):

$$\alpha_t = \frac{\sigma}{\sigma_n} = \frac{K}{\sigma_n\sqrt{(2\pi r)}} \tag{4}$$

Substituting (2) into (3),

$$\epsilon = \epsilon_n\alpha_\epsilon = \epsilon_n\left\{\frac{K}{\sigma_n\sqrt{(2\pi r)}}\right\}^{2/(n+1)} \tag{5}$$

where ϵ is the strain at the distance r from notch tip

The strain rate becomes

$$\dot\epsilon = \dot\epsilon_n\left\{\frac{K}{\sigma_n\ \sqrt{(2\pi r)}}\right\}^{2/(n+1)} \tag{6}$$

or

$$\log \dot{e} = \log \dot\sigma_n + \frac{2}{n+1}\log\left(\frac{K}{\sigma_n}\right) \tag{7}$$

where $\dot{e} = A\dot\epsilon,\ A = E\ (2\pi r)^{1/(n+1)}$.

Here A is assumed to be material constant and e is termed as 'strain rate parameter'.

In the following the expressions necessary for the approximate calculation of strain rate parameter will be given for the three types of specimens.

(1) Tension Test

The stress intensity factor in the tension test specimen which has the notch depth, c and the breadth, $2b$ is

$$K = \sigma\sqrt{(\pi c)}\sqrt{\left(\frac{2b}{\pi c}\tan\frac{\pi c}{2b} + 0{\cdot}1\sin\frac{\pi c}{2b}\right)} \tag{8}$$

In this case, $\dot\sigma_n$ is calculated as (average loading rate)/(gross area).

(2) Slow bend test

Four points loading was employed (Fig. 1). The stress intensity factor in this case has been given by Yoshiki, Kanazawa and Machida [9] as follows. .

$$\begin{aligned} K &= k\sigma_n\sqrt{(2b)} \\ &= 3k\sqrt{(2b)}\ l_1P/\{4tb^2m(x_0)\} \end{aligned} \tag{9}$$

where k: constant, σ_n: nominal fibre stress corresponding to the load at the crack initiation, t: plate thickness, $m(x_0) = M(x_0)/M(O)$, M: Spring constant ($P = Mx$), l_1: span shown in Fig. 1.

The stress rate $\dot\sigma_n$ is

$$\dot\sigma_n = \frac{3l_1\dot{P}}{4tb^2m(x_0)} \tag{10}$$

(3) Charpy type impact bending test

The stress intensity factor is

$$K = \frac{3k\sqrt{(2b)}P}{8tb^2m(x_0)} \tag{11}$$

where P is expressed as follows.

$$P = \dot{P}\delta t = M(c_0)\dot{l}\delta t \tag{12}$$

Assuming that $\dot{l}$ is equal to the Charpy hammer striking speed, v, equation (12) is reduced to

$$P = M(c_0)v\delta t \tag{13}$$

According to a previous work [10] the hardening exponent, n, of the mild steel tested is estimated to be about 0·170. After substituting some values in above equations, the relationship between the strain rate parameter, $\dot{e}$ and the critical C.O.D. Φ_c is shown in Fig. 12.

This figure shows that the logarithm of Φ_c decreases linearly with the logarithm of $\dot{e}$ up to log $\dot{e} \sim 2$. This qualitatively agrees with the well-known relative equivalence of the logarithm of strain rate to the reciprocal of absolute temperature (see Figs. 5 to 7).

Since the above consideration is based on the approximate calculation, more accurate calculation is still required to establish quantitatively the relation between strain rate and critical C.O.D. in gross yield condition. From this discussion, however, the critical C.O.D. significantly depends on the strain rate at the tip of notch as well as temperature. Thus Φ_c is to be expressed in terms of temperature, parameters of strain rate and plastic geometry, plastic deformation characteristic values of the material concerned such as yield stress, strain hardening exponent etc.

Conclusions

(1) The 'double notch test' is shown to be a very useful method to measure the critical C.O.D. Because the variation of the root radius of slit by conventional machining does not affect on the onset of brittle crack propagation, then from the use of microphotographs the critical C.O.D. can be relatively simply and directly measured.

(2) The 'over-all displacement' method for C.O.D. measurement would be important for its simplicity in test procedure. But the over-all displacement is apt to contain significant components other than true C.O.D. value At present any theoretical and simple relation with general applicability to evaluate C.O.D. from over-all displacement has not been established. This is of much importance as a future problem in relation to commercial and/or screening test methods.

(3) The C.O.D. has the Arrhenius type temperature dependence irrespective of geometry of specimen, loading system, loading rate, etc. But these parameters affect the level of Φ_c value.

(4) The three types of the 'double notch test' adopted in the present work yield different Φ_c values at the same temperature. As the first step this is explained quantitatively by considering the strain rate in the zone close to notch tip.

(5) The procedure of analysis should be improved in future. The critical C.O.D. for a certain material will be well formulated in terms of temperature, characteristic values of plastic deformation of the material (e.g. yield stress, strain hardening exponent, etc.) and geometric parameters of notch or defect or structural discontinuity including proper plastic constraint factor.

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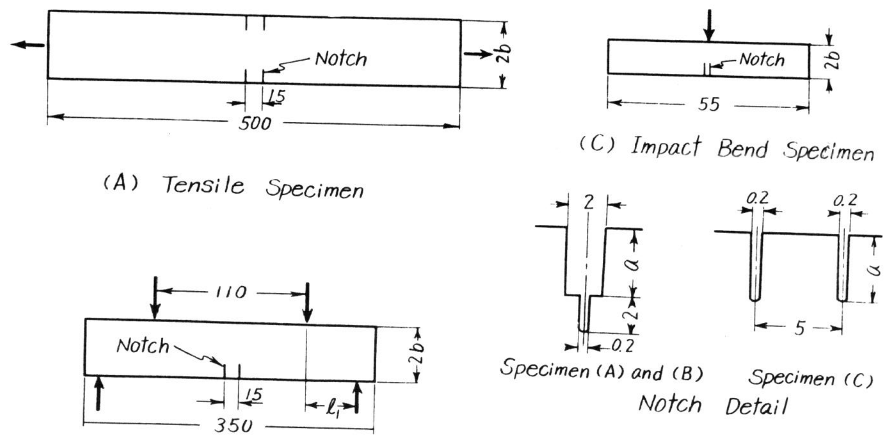
Table 1.
Typical variation of notch root radius.

	Chemical composition (%)					Mechanical properties		
	C	Si	Mn	P	S	Yield point (kg/mm^2)	Tensile strength (kg/mm^2)	Elongation (%)
Mild Steel (SM 41)	0·17	0·30	0·87	0·018	0·019	26·0	44·0	35·0

Table 2.
Chemical compositions and mechanical properties of the test material.

Specimen	Notch no.	Initial state	After loading	Critical COD
A (−55°C)	1	0·227	0·658	0·431
	2	0·242	Fracture	—
	3	0·300	0·686	0·386
	4	0·261	Fracture	—
B (−30°C)	1	0·308	Fracture	—
	2	0·305	0·716	0·411
	3	0·311	Fracture	—
	4	0·269	0·881	0·612



	Tensile Specimen		Slow Bend Specimen			Impact Bend Specimen	
a	7	18	2	2	8	2	3
2b	90		20	40	60	10	

(Unit mm)

Fig. 1. Double notch test specimens.

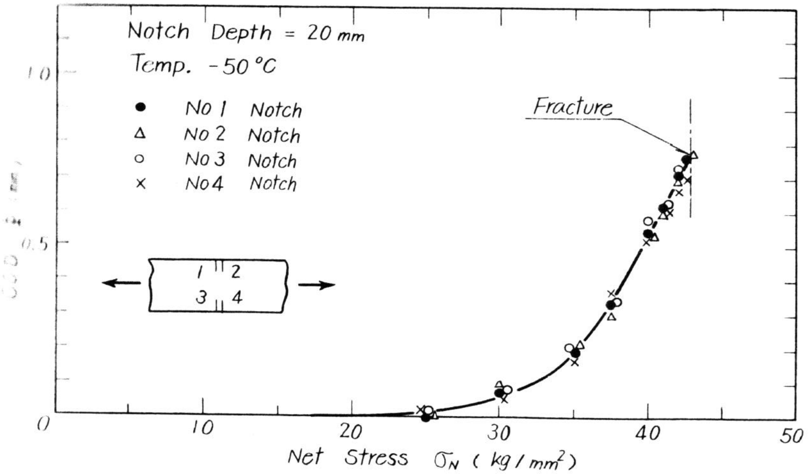


Fig. 2. Relation between C.O.D. Φ and net stress.

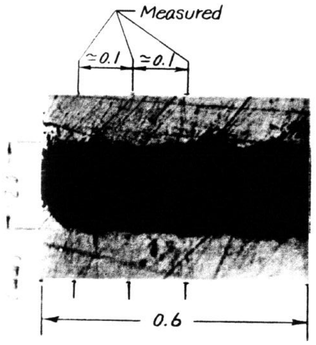


Fig. 3. Detail of notch tip.

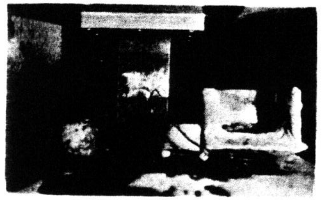


Fig. 4. Double notch tensile test.

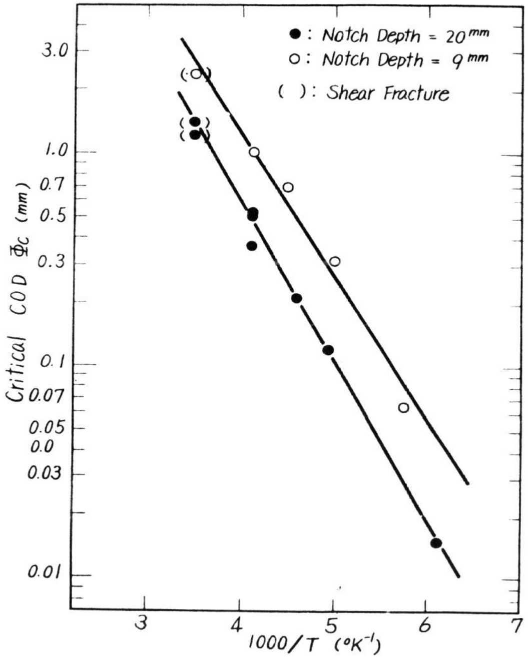


Fig. 5. Relation between critical C.O.D. and temperature (tensile test).

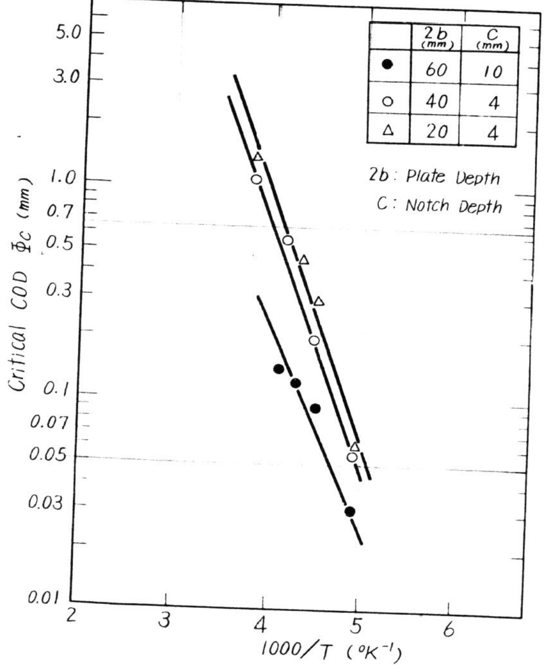


Fig. 6. Relation between critical C.O.D. and temperature (slow bend test).

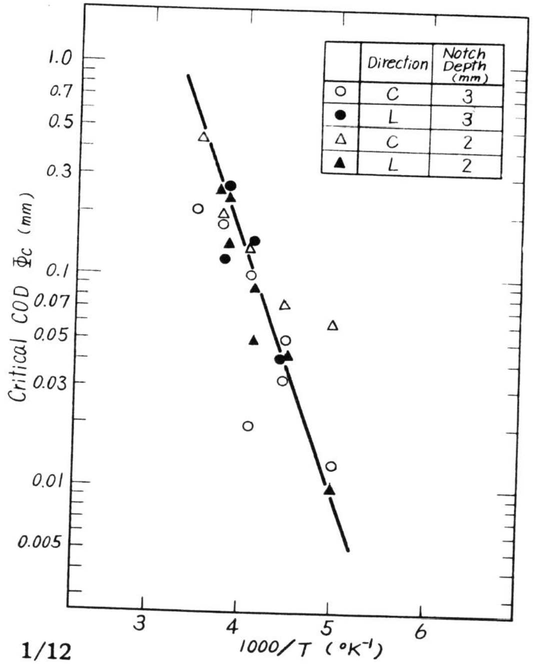


Fig. 7. Relation between critical C.O.D. and temperature (impact bend test).

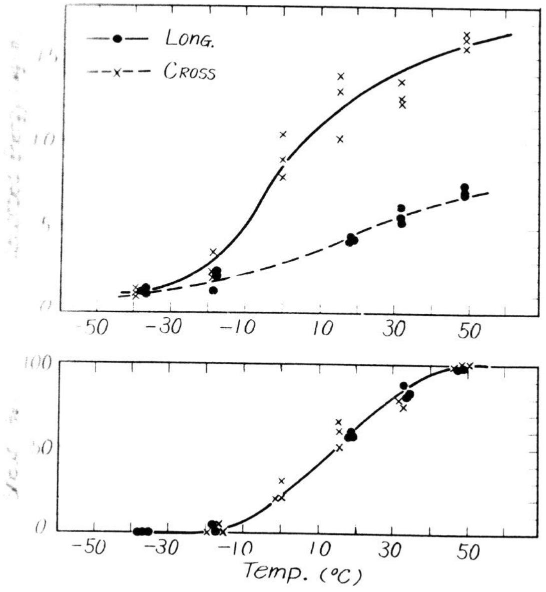


Fig. 8. 2 mm. V Charpy transition curves.

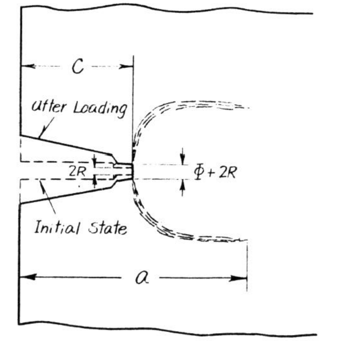


Fig. 9. Detail of crack opening.

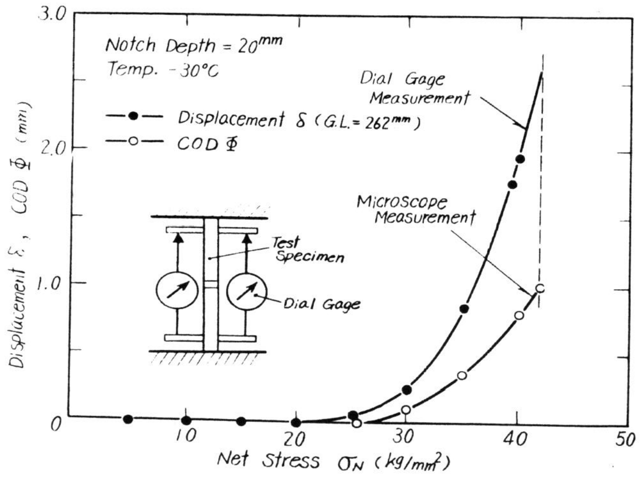


Fig. 10. Comparison overall displacement with directly measured C.O.D.

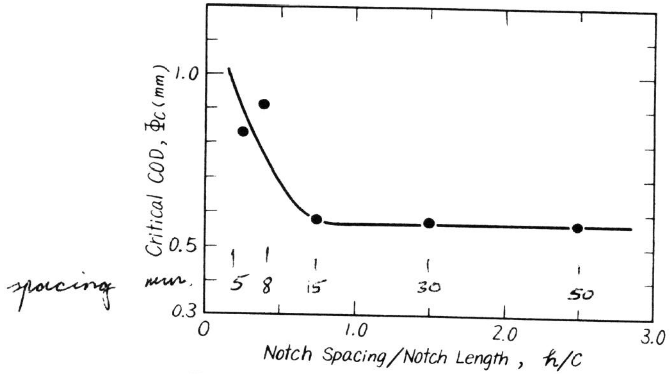
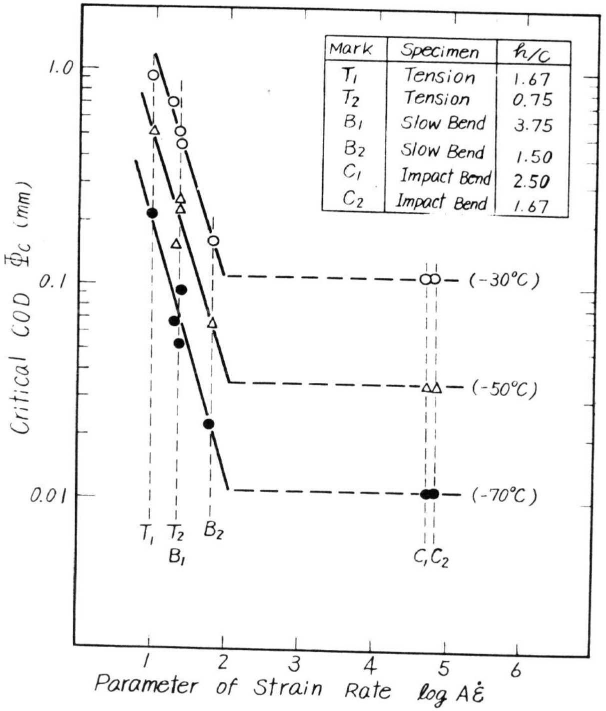


Fig. 11. Interaction of two parallel cracks.



Mark	Specimen	h/C
T_1	Tension	1.67
T_2	Tension	0.75
B_1	Slow Bend	3.75
B_2	Slow Bend	1.50
C_1	Impact Bend	2.50
C_2	Impact Bend	1.67

Fig. 12. Effect of strain rate on critical C.O.D.