DEVELOPMENT OF FATIGUE CTOD TEST FOR INVESTIGATION OF BRITTLE REGIONS IN WELDED JOINTS

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ABSTRACT

In order to detect the minimum CTOD value in welded joints easily, Fatigue CTOD test method was developed. In this test, a CTOD test specimen is tested at low temperature under cyclic loading which makes a fatigue crack scan in any part of welded joints. This new method makes it possible to find the minimum CTOD value by a few specimens. The new method can be applied to study on the location of the brittle zone, reason of embrittlement and other purposes.

Furthermore, the relationship between ordinary fracture toughness and fatigue fracture toughness by this new test method is investigated from the viewpoints of the cyclic stress ratio, the loading rate and the plastic zone size. It became clear that the larger the cyclic stress range was, the larger the fatigue fracture toughness was. The fatigue fracture toughness conformed well to the ordinary fracture toughness when the cyclic stress range was small. It was non-sensitive to the loading rate. The fatigue CTOD test should be carried out with a small cyclic stress range and with the cyclic frequency up to 10 Hz in order to evaluate the fracture toughness of welded joints.

KEYWORDS

Brittle fracture, fatigue, toughness, weld heat affected zone, low temperature steel, cyclic plastic zone, hot strain embrittlement, CTOD test, loading rate.

INTRODUCTION

The crack tip opening displacement (CTOD) approach based on elastoplastic fracture mechanics has widely been used for material selection and weld defect evaluation to maintain structure safety against fracture initiation, after the testing method was established in early 1970s. In order to assure the integrity of welded structures it is primarily important to know critical CTOD (δ_c) values of the most embrittled regions in the welded joins, although comprehensive investigation should also be made from other viewpoints, including probability study on nucleation of serious defects, crack arrest toughness and structural redundancy. However the results of CTOD tests on heterogeneous materials such as welded joints show substantial scatter because the crack tip samples different microstructures in each specimen. This scatter makes it difficult to determine the lowest δ_c values of welded joints and also prevents real analysis of structural safety. For the purposes of revealing the local fracture toughness of the brittle regions in welded joints and analysing its significance the development of a simple test method which enables precise detection of the lowest δ_c of heterogeneous materials with a limited number of specimens has been desired for a long time.

The present authors already proposed (Tanaka, 1982), as one of strong candidates for this object, application of fatigue fracture toughness test method by which researchers (Yokobori, 1970) has been investigating damage by fatigue loading to fracture toughness. The authors' standpoint was that this method can be used, instead of the ordinary CTOD test of monotonic loading type, for detecting the minimum fracture toughness with single or a few specimens since a crack tip in this method travels inside the test materials and scans various microstructures during one test. To eliminate extensive fatigue damage on the material, however, further fracture mechanical investigations seem to be required.

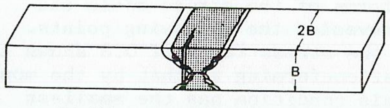
In the present report, results of research in terms of this point are described.

FRACTURE TOUGHNESS OF WELDED JOINTS - BACKGROUND -

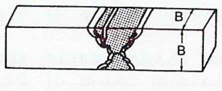
Figure 2 illustrates an example of CTOD test results for a welded joint. This figure shows that face cracked specimens (as in Fig. 1) resulted in a wider scatter and a lower minimum value of δ_c than side cracked specimens (also as in Fig. 1). From the subsequent investigation on microstructure of the specimen which showed the minimum value of δ_c, the following points have been clarified.

(i) The fatigue crack tip at the fracture initiation point of the face cracked specimen was confluent with the grain coarsened heat affected zone adjacent to the weld fusion line.

(ii) Even though fatigue cracks in side cracked specimens were intersecting the grain coarsened heat affected zone, δ_c values obtained were higher than the minimum value of δ_c from face cracked specimens.



(a) Side cracked specimen



(b) Face cracked specimen

Fig. 1. Specimens for the CTOD tests for welded joints

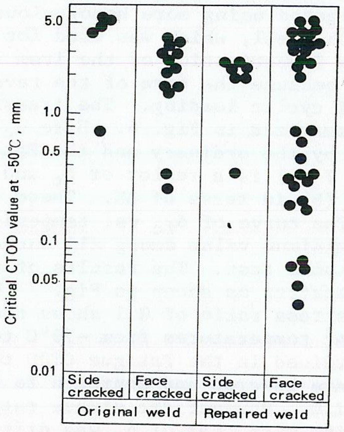


Fig. 2. Examples of the ordinary CTOD test results for SMAW joints of Al killed fine grain steel

(iii) Considerably wide contact (say 2mm) between the fatigue crack tip and the most embrittled region such as the grain coarsened heat affected zone seems to be necessary to lead the lowest value of δ_c.

From these facts, it is considered that the result by side cracked specimens shows a sort of a mean value of δ_c in the welded joint and that by face cracked specimens shows the fracture toughness of a local region. In order to detect the local fracture toughness of the most embrittled zone in a welded joint, the fatigue crack tip has to be controlled so that it contacts with the aimed region. However the brittle region in welded joint is very limited in the length and width because of a normalizing effect by subsequent weld thermal cycles and depression effect by aluminum nitride precipitate to grain growth. As mentioned above, the following points have been the serious problem in the subject.

(i) It is difficult to evaluate the local fracture toughness such as of the most embrittled zone in a welded joint.

(ii) It is still unknown to what extent the fracture toughness of very localized regions affects the safety of the structure.

FATIGUE CTOD TESTING METHOD

In order to overcome the problems described above, Fatigue CTOD test has been developed. An outline of this test method is shown in Fig. 3. In this test a specimen is tested, at low temperature as aimed, under cyclic loading which extends a fatigue crack from the initial kerf toward the heat affected zone through the weld metal.

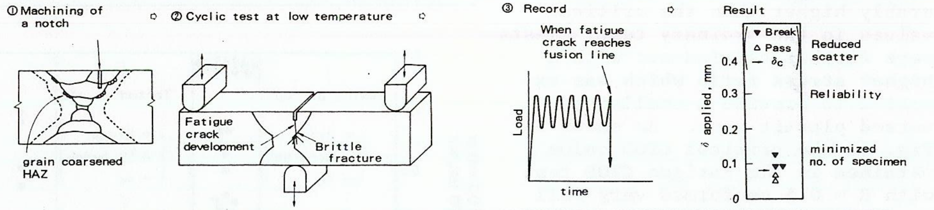


Fig. 3. Testing procedure of the Fatigue CTOD test

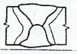
When the fatigue crack tip reaches close to the embrittled zone, brittle fracture may take place in the case where the applied CTOD value is larger than the critical value of the weakest region. When the applied CTOD is smaller than the critical CTOD value, a specimen will not be broken and a fatigue crack will propagate through the zone. The lowest value of δ_c can be expected to lie between the CTOD values calculated on these two specimens. In general, Fatigue CTOD test employs face cracked specimens having a initial notch of 0.15 mm wide slit with its tip 2 mm above the fusion line. The specimens are tested in a servo-hydraulic testing system under load control. For specimens which showed brittle fracture, CTOD value calculation was made using the applied load, total clip gauge displacement and crack length measured on the fracture surface. Because loads at brittle fracture initiation recorded by a transient recorder generally conformed to the programmed maximum loads, the latter were used for the calculation when high speed recording had not been made. The total clip gauge displacement was chosen for the CTOD calculation from the same hypothesis as in Garwood's J-resistance curve theory (Garwood, 1975). For specimens which did not show brittle fracture when fatigue crack passed the brittle zone, the distance between the fusion line and the upper surface which was measured on cross-sections extracted from the specimen was regarded as crack length for the CTOD calculation. The total clip gauge displacement at a point, where a cyclic amplitude of the displacement agreed with a theoretical value calculated by a compliance equation (Tada, 1973), was adopted for CTOD determination. The compliance equation was a little modified so that it agreed with the experimental compliances at the beginning of test and the last loading for which crack lengths were known. When the recorder used could not follow the quick change in the out-put of a clip gauge because high frequency loading was employed, intermittent slow loadings were introduced in the programme.

RESULTS OF FATIGUE CTOD TEST ON WELDED JOINTS AND DISCUSSION

The welded joints used are shown in Table 1. Ordinary CTOD tests and Fatigue CTOD tests have been carried out with face cracked specimens on both of joints A and B. Figure 4 shows test results. When the joints were tested with a stress ratio R (= P_{min}/P_{max}) of 0.1, fatigue cracks penetrated grain coarsened heat-affected zones without causing brittle fracture at a maximum load corresponding to CTOD values considerably higher than the critical values in the ordinary test. Tests were further carried out with a higher stress ratio which was expected to provide a smaller reversed plastic zone. As shown in Fig. 4, the critical CTOD value obtained in the Fatigue CTOD test with R = 0.5 conformed very well to the minimum δ_c in the ordinary CTOD test.

Figure 5 shows relationships between the cyclic amplitude of stress intensity factor (ΔK) and the ratio of the applied CTOD value to the minimum value of δ_c obtained in the series of test. This arrangement indicates that the lowest value of δ_c cannot be obtained when the Fatigue CTOD test is carried out with a ΔK higher than approximately 1300 $N/mm^{1.5}$, and that a smaller ΔK value in the Fatigue CTOD test is preferable to obtain the minimum value of δ_c.

Table 1. Welded joints for CTOD test

Mark	Steel Material	Welding method	Heat input (KJ/cm)	Sketch of section
A	Fine grain low temperature steel.	SMAW with 3-repares (Multipass vertical up)	~30	
B	High tensile strength steel. (HT60)	EGW (VEGA) (Vibratory electrode-gas welding)	63~75	
C	Fine grain low temperature steel.	SMAW with 3-repares (Multipass vertical up)	35	
D	Fine grain low temperature steel. (Ti treatment)	SAW (One Pass tandem welding)	69	

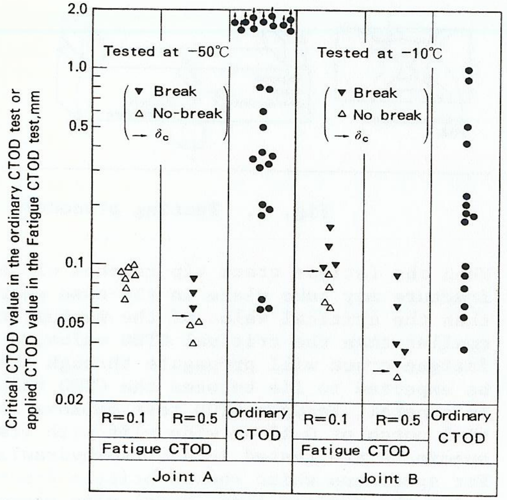


Fig. 4. Test results for welded joints by the Fatigue CTOD and the ordinary CTOD tests

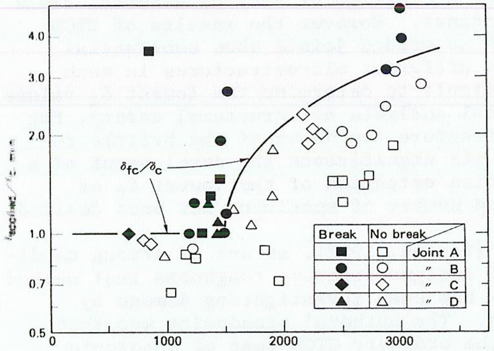


Fig. 5. Influence of ΔK value to the minimum value of δ_c obtained in the Fatigue CTOD test

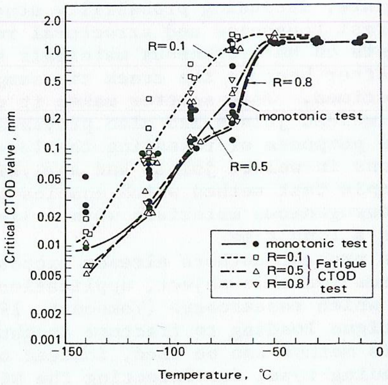


Fig. 6. Comparison of δ_c and δ_{fc} transition curves for the base plate of HT60

EFFECTS OF TEST CONDITION

In order to make clear the fracture phenomenon in the Fatigue CTOD test and its differences to that in the ordinary CTOD test, the following investigations were conducted.

(A) Whether or not the reversed plastic zone caused by cyclic loading in the Fatigue CTOD test affects the lowest value of δ_c also in homogenious materials.

(B) Whether or not the lowest value of δ_c in the Fatigue CTOD test depends on the cyclic frequency.

Because specimens from welded joints having heterogeneous microstructures and wide scatter of δ_c are not suitable for the item (B), both problems were investigated using more homogenious base plate. A 600 N/mm^2 class high strength steel, which was used for joint B, were applied.

For the investigation of the item (A), the stress ratio was varied from 0.1 to 0.8 because the size of the reversed plastic zone depends on the amplitude of cyclic loading. The transition curves of δ_c by both of the methods are summarized in Fig. 6. Here δ_c and δ_{fc} refer to the critical CTOD values by the ordinary and the Fatigue CTOD test methods, respectively. Figure 7 (a) is a replot of δ_c and δ_{fc} in terms of the stress ratio and Fig. 7 (b) in terms of ΔK. These results revealed the following points.

(i) The curve of δ_{fc} vs. temperature for the stress ratio of 0.8 shows the minimum value among all curves, almost conforming to that by the monotonic test. The results of δ_{fc} in this condition has the smallest scatter as shown in Fig. 7 (b). On the other hand, the curve for the stress ratio of 0.1 shows the upper value of them.

(ii) At temperatures from −70°C to −110°C, the minimum values of δ_{fc} obtained in the Fatigue CTOD test depends on the stress ratio. These are lowered and approach to those of δ_c as the stress ratio approaches 1.0. However the stress ratio to have the minimum value of δ_{fc} agreeing with that of δ_c was different for each of temperature.

(iii) At lower temperature as −140°C the minimum value of δ_{fc} was lower than that of δ_c though the effect of the stress ratio was observed in the same way as at higher temperatures.

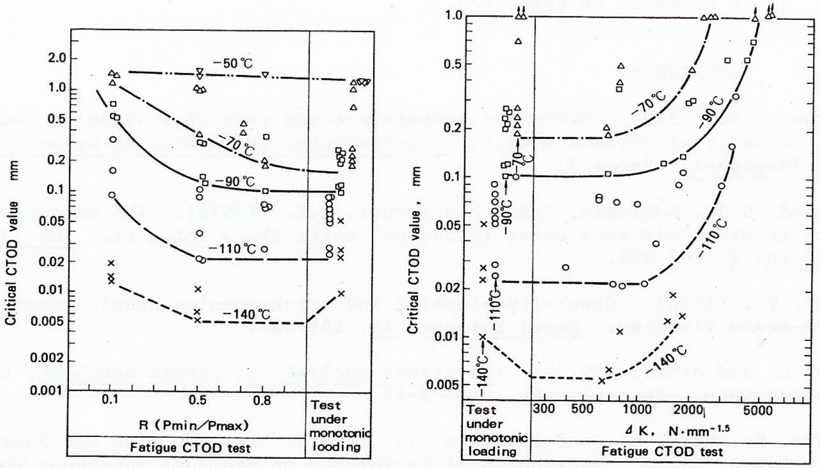
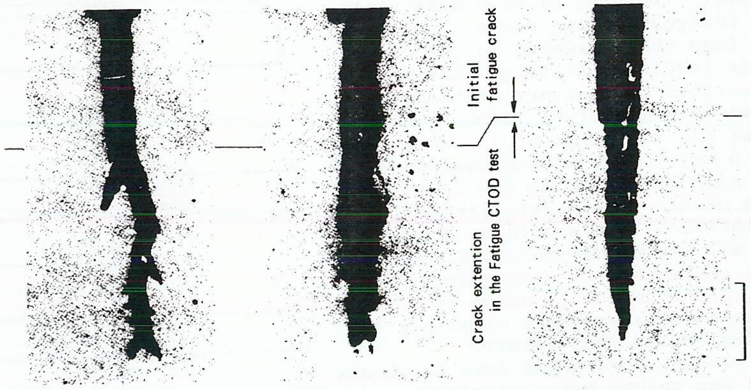


Fig. 7. Effects of R ratio and ΔK on δ_{fc} for the base plate of HT60

(iv) As shown in Fig. 7 (b) the minimum value of δ_{fc} coincided well with that of δ_c when the Fatigue CTOD test was carried out with a ΔK value less than approximately 1000 $N/mm^{1.5}$ at any testing temperature except −140°C.

It is not clear at this stage what the real reason controlling the effects of cyclic loading on the resulting δ_{fc} is. Both of crack closure and the reversed plastic zone may be important factors. Since crack closure during an unloading stage in cyclic loading may be attributed by R ratio and the size of the reversed plastic zone is controlled by ΔK, it seems necessary to choose appropriate values of R and ΔK in the Fatigue CTOD test. After the rearrangement of data, shown in Figs. 7 (a) and (b), an R ratio equal to or over 0.5 and ΔK equal to or less than 1000 $N/mm^{1.5}$ seem to be recommended. Investigation in this area, i.e., fracture mechanical and physical-metallurgical investigation together with realistic assessment of fatigue loading effects on subsequent fracture toughness seems necessary because of their importance not only to establishment of the Fatigue CTOD test method but also to assessment of safety of actual structures for which cyclic loading is expected to apply. Figure 8 is an example of studies for this purpose and shows the feature of crack propagation and the plastic zone caused by cyclic loading. Here the recrystallization (Shoji, 1976) was used. The recrystalized area shows the plastic zone having the strain of approximately 0.2. All specimens were tested at −70°C with the same maximum load until the fatigue cracks developed by the same distance from the tip of the sawn notch. ΔK values of 640 $N/mm^{1.5}$, 1500 $N/mm^{1.5}$ and 2500 $N/mm^{1.5}$ were applied. This figure shows that consecutive plastic zone and a fairy sharp crack tip are maintained when the loading programme met requirements proposed above.

For investigation of item (B) described above the Fatigue CTOD tests with various cyclic loading rates from 0.1 to 30 Hz were carried out. In this series of test transient recorders were used for accurate recording of loading rate at the moment of brittle fracture initiation. The ordinary CTOD tests were also carried out with various loading rates to compare the sensitivities to the loading rate in δ_{fc} and δ_c. Figure 9 shows the relationships between δ_{fc} and frequency of cyclic loading in the Fatigue CTOD test. It is clear that δ_{fc} is little affected by the frequency of cyclic loading. Figure 10 is a replot of δ_{fc} in terms of the loading rate at the moment of brittle fracture initiation and the results of the ordinary CTOD test with high loading rate. The curve predicted by Barsom's equation (1976) is also shown in this figure. In the records of the loading rate in the Fatigue CTOD test there were some cases where brittle fracture took place at the moment when the load began to decrease just after passing the maximum load level. But the loading level at the moment of brittle fracture initiation could be regarded as to be equal to the maximum load within the accuracy of 3%. From this figure, it becomes clear that δ_{fc} is independent of the loading rate at the moment of brittle fracture initiation. δ_{fc} seems to be nonsensitive to the rate. Although the exact reasons of this fact are not again clear, the fact that the specimen has already deformed before the last cycle of loading may be an important element. Only a small portion ahead the existing plastic zone is newly deformed by the last cycle and the preexisting plastic zone must be the measure of toughness. From these results, it is clear that the frequency up to 10 Hz is permissible in the Fatigue CTOD test.



ΔK=2500 N·mm⁻¹·⁵ R=0.1 ΔK=1500 N·mm⁻¹·⁵ R=0.5 ΔK=640 N·mm⁻¹·⁵ R=0.8

Fig. 8. Features of fatigue crack propagation in the cross section of the base plate of HT60

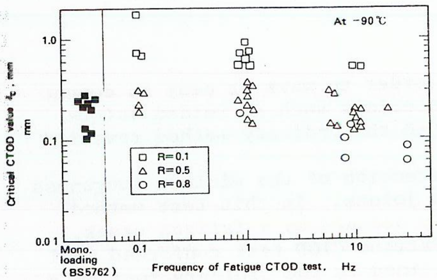


Fig. 9. Relationships between cyclic frequency and δ_{fc} in the Fatigue CTOD test for the base plate of HT60

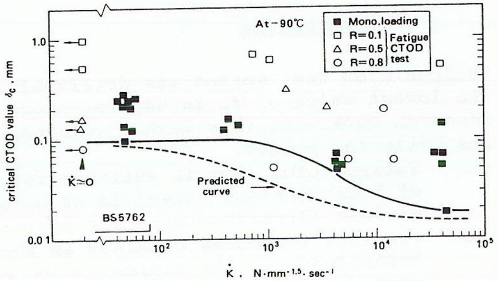


Fig. 10. Relationships between the loading rate at the moment of brittle fracture initiation and δ_{fc} for the base plate of HT60

DISCUSSIONS

Although face cracked CTOD specimens from actual weld joints, have been mainly employed in the present series of investigation, other types of configuration may easily be designed after metallurgical consideration on where the weakest microstructure locates. Figure 11 shows examples of modification of the specimen geometry. When a big degradation in toughness by temper embrittlement is expected on a grain coarsened heat-affected zone, type (a) may be a suitable specimen. When all the microstructures have to be tested, type (b) or (c) may be adequate. By this kind of modification, specimen numbers in various industrial qualification tests may be reduced without loosing reliability.

As for the effect of loading conditions in the Fatigue CTOD test, there are various points to be studied. It is surprising to know that a very weak zone "vanishes" when a small R ratio is applied. There were cases where a low δ_c failure also vanished after only one unloading for a rest for the operator. Not only mechanical effects as crack closure, but also changes of metallurgical characteristics as dislocations in the microstructure may have to be investigated. Figure 8 showing regions of high deformation may also be curious. The size of high deformation zone in fatigue loading seems to be smaller than that produced by the first monotonic loading. Although this may be well described by fracture mechanics, agreement of temperature transition curves of δ_{fc} with that of δ_c, as shown in Fig. 6 may not be easily described by it. Also on Fig. 8 it can be stressed that the nature of recrystallization have to be clarified. It should be studied whether all the highly deformed zone is shown by the method or only a deformation under single monotonic loading is shown. There seems to be a number of points to be studied in the near future. Nevertheless authors would like to stress that the new method has a prominent future and can be applied in various areas including material research and industrial assessment.

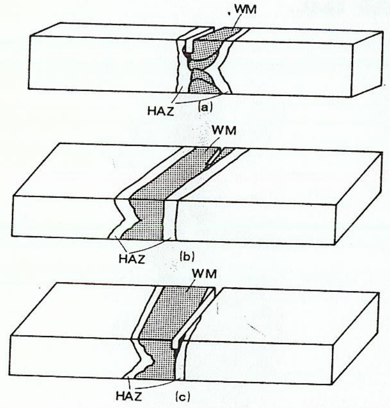


Fig. 11. Fatigue CTOD test specimens for detection of the minimum fracture toughness on welded joints

CONCLUSION

Fatigue CTOD test method was developed in order to make it easy to detect the lowest value of δ_c in heterogeneous materials such as welded joints. Research work with this method together with the ordinary method revealed the following points.

(i) Fatigue CTOD test is suitable for detection of the minimum toughness of heterogenious materials as welded joints. In this test method various microstructures are certainly scanned by a fatigue crack.

(ii) Fracture toughness obtained in the Fatigue CTOD test conformed well coinsided with the minimum value obtained in the ordinary test on a numerous number of specimens.

(iii) The Fatigue CTOD test should be carried out with a ΔK value less than 1000 N/mm$^{1.5}$ and a stress ratio R greater than 0.5.

(iv) Fracture toughness by the Fatigue CTOD test is less sensitive to the loading rate than that by the ordinary method. The loading rate up to 10 Hz seems to be permitted.

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APPENDIX: CTOD CALCULATION IN THE FATIGUE CTOD TEST

Figure A.1 shows the schematic records of load vs. displacement ((a)) and displacement vs. time ((b)) relationships. At the beginning of the test a specimen was loaded and unloaded along I and I' down to the point B in Fig. A.1 (a). After this point, cyclic loadings from P_{min} to P_{max} were applied and the relationship between the displacement and time were recorded as in Fig. A.1 (b). When the fatigue crack tip reached the brittle region, brittle fracture might take place and the load vs. displacement curve along II' would be recorded. On the fracture surface the final fatigue crack length could be measured as a_f. Applying the same hypothesis as Garwood's J-resistance curve theory (1975), the load vs. displacement record for a notional specimen with an initial crack length a_f might be assumed to be represented by line II in Fig. A.1 (a). The load vs. time record at the moment when brittle fracture took place was shown in Fig. A.2. The fracture load was regarded as the programmed maximum load. After these assumptions the CTOD value calculation was made using the applied load, total clip gauge displacement and crack length measured on the fracture surface in accordance with BS5762 standard. In the case of a specimen which did not show brittle fracture when the fatigue crack passed the brittle region, the distance between the brittle region such as the welded fusion line and the upper surface of the specimen measured on a cross section extracted after the test was used for the crack length in the CTOD calculation. On the record of clip gauge opening displacement vs. time, the crack length extention was monitored through the cyclic amplitude of the clip gauge displacement, ΔVg, as a measure of compliance. Therefore the total clip gauge displacement, Vg, at a point where the cyclic amplitude of the displacement agreed with the value calculated by a compliance equation could be used in the CTOD calculation. Present series of the experiment made use of the compliance equation by Tada (1973) with some modifications.

$$\frac{\Delta Vg}{\Delta P} = \alpha\beta\frac{24a}{BW^2}\{0.76 - 2.28x + 3.87x^2 - 2.04x^3 + \frac{0.66}{(1 - x)^2}\}$$

$$\alpha = \frac{0.45W + 0.55a + Z}{0.45W + 0.55a}, \text{ (correction for knife edge height Z)}$$

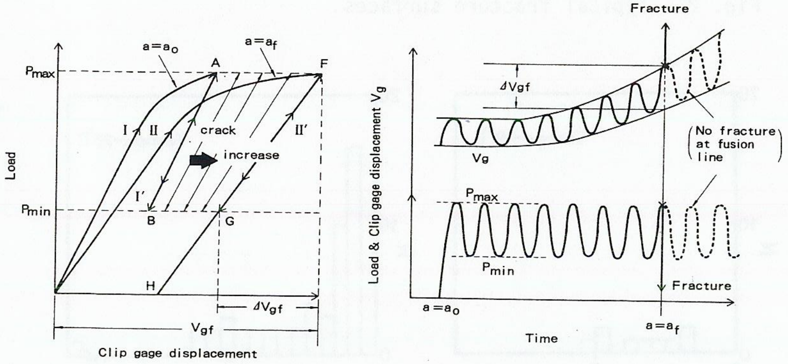
β: Experimental correction factor from initial compliance for a_o

and

$$\Delta Vg/\Delta P = \Delta Vg/(P_{max} - P_{min})$$

$$x = a/W$$

The compliance equation was slightly modified so that it might agree with the experimental compliance at the beginning of a test. An intermittent slow loading programme in each 100 cycles was introduced in order to enable an accurate monitoring of the displacement change, ΔVg, when the high frequency loading was employed and the recorder used could not follow the quick change in Vg output.



(a) Load-displacement curve

(b) Test record

Fig. A.1 Schematic test records in the Fatigue CTOD test

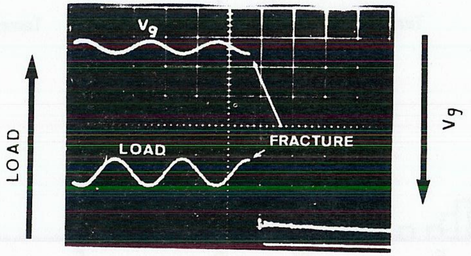


Fig. A.2 Load and clip-gauge-opening records by transient memory