FCP Report No. 28

EVALUATION OF FRACTURE MECHANICS PARAMETERS FOR A27 CAST STEEL

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Abstract

The fracture toughness of an A27 cast steel was evaluated using the J-integral approach. The effect of range of stress intensity factor on fatigue crack growth rate was also determined. In the course of the study a more accurate method of establishing the existing crack length through a compliance technique was also developed.

An effort was made to review the critical concepts of linear elastic fracture mechanics for "valid" K_{Ic} testing, J-integral method for toughness testing, and fatigue crack growth rate for conditions of cyclic loading.

A Report of the
FRACTURE CONTROL PROGRAM

College of Engineering, University of Illinois
Urbana, Illinois 61801
December, 1977

ACKNOWLEDGMENTS

This investigation was conducted in the H. F. Moore Fracture Research Laboratory, of the Department of Theoretical and Applied Mechanics, University of Illinois, Urbana. Financial support was provided by the University of Illinois Fracture Control Program which is directed by Professor H. T. Corten. Sponsors of this program include Caterpillar Tractor Company, Clark Equipment Company, Deere and Company, Eaton Corporation, Exxon Production Research Company, General Motors, International Harvester Company, and Rexnord. Electro-Motive Division of General Motors supplied the cast steel used in this investigation from a single "heat" cast at Rockwell International Foundries.

The author wishes to thank his advisor, Professor G. M. Sinclair, for valuable discussions and continual encouragement throughout this investigation.

Finally, the author wishes to thank Mrs. Darlene Mathine, who typed all drafts of the manuscript.

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INTRODUCTION

During recent years, applicability of linear elastic fracture mechanics to situations involving high strength, brittle metals, has proven successful. It is also desirable to apply the fracture mechanics technology to situations involving low yield strength, ductile metals, provided thickness and other constraints are sufficient to provide plane-strain conditions.

It is often difficult, due to sample size, to satisfy the validity tests for plane-strain fracture toughness (ASTM E399-72) [1] for metals which exhibit low yield strength and high ductility. With this in mind, researchers have directed their efforts toward finding an alternative technique to evaluate the fracture toughness of these materials. The J-integral, proposed by Rice [2], is presently being explored as a possible solution to this problem.

The J-integral has been used successfully by Begley and Landes [3,4,5] as an elastic-plastic fracture criterion. In this technique a compact tension specimen (Fig. 1), with a deep crack ($B/b > 1.25$), is loaded until fracture occurs, and J is determined from the expression

$$J_{Ic} = \frac{2A}{Bb} \qquad (1)$$

where A is the area under the load-deflection record taken at the point of crack extension, B is the thickness, and b is the length of the uncracked ligament. The J_{Ic} fracture criterion has a direct correspondence to K_{Ic} by the relation

$$J_{Ic} = G_{Ic} = \frac{1 - \nu^2}{E} K_{Ic}^2 \qquad (2)$$

(Refer to Appendix A for further information on J-integral theory.)

The validity of this relation has been supported by Begley and Landes where up to 12-inch thick specimens were used for K_{Ic} evaluation. These values of K_{Ic} compared favorably in Eq. 2 to the value of J_{Ic} found for the same material at the same temperatures. The advantage in using the J technique is that a much smaller specimen may be used to evaluate fracture toughness. Conceivably, using this analysis, the fracture toughness evaluation of a low yield strength, ductile material no longer would be a difficult task.

Object and Scope

The purpose of this investigation was to evaluate the toughness properties of a low strength, highly ductile, cast steel so that the technology of fracture mechanics might be applied to insure against fracture. In order to use this technology in an efficient manner, data in two areas must be available. A knowledge of the fracture toughness over a large temperature range and data on fatigue crack growth rate versus range of stress intensity factor must be accessible.

Since an A27 cast material (see Table 1) is a low yield strength, highly ductile material, it was evaluated in the areas of fracture toughness and fatigue crack growth rate. The toughness was evaluated in a temperature range from -250°F to +200°F, and the fatigue crack growth rate was investigated over a stress intensity range from 12 ksi$\sqrt{in}$ to 60 ksi$\sqrt{in}$.

It was also desirable to develop a new technique for more accurate crack measurement during fatigue cracking. An effort was made to more accurately define crack length using a "compliance" technique.

THEORY OF APPLICATION

Design of structural members, using the linear-elastic fracture mechanics, is basically a stress intensity consideration where limits are established for crack instability. The essence of this analysis lies in relating the nominal stress to the stress field near the tip of the crack.

Stress Intensity Factor

The stress field near the tip of the crack for Mode I opening can be described by a single parameter, K_I, which is commonly referred to as the stress intensity factor. Values of K_I are dependent on such factors as the geometry of the member being loaded, the length of the given crack, and the magnitude of the loads being applied.

For brittle fracture, in the presence of cracks or crack-like defects, the stress intensity factor, K_I, may be considered to have reached a limiting value called K_{Ic}. Since the crack tip stress has different limits for different materials, the value of K_{Ic} can be treated as a material property (6). Therefore, K_{Ic} is a quantitative measure of the material's ability to withstand fracture in the presence of cracks. Consequently, K_{Ic} is given the designation plane strain fracture toughness.

The stress intensity factor is a function of the applied load and the crack length, and it may be represented in the form:

$$K_I = C\sigma\sqrt{\pi a} \tag{3}$$

where σ = nominal stress

a = crack length

C = a crack geometry factor

According to this relation the value of K_I increases if σ and a are increasing, if σ remains constant and a increases, or if a remains constant and σ increases. The stress intensity factor, K_I, may therefore increase to a limiting value, K_{Ic}. At this point, crack instability (fast fracture) occurs.

Crack Growth Rate

If cyclic loading is applied, the crack will grow at a rate that is a function of the range of applied stress intensity factor, $\Delta K_I = (K_{max} - K_{min})$. The cyclic growth rate, da/dN, is also a material property and can be related to the stress intensity factor by the power equation

$$\frac{da}{dN} = C_o(\Delta K)^m \qquad (4)$$

where C_o = a material and test environment constant

ΔK = stress intensity range, $(K_{max} - K_{min})$

m = growth exponent, a material constant for non-corrosive environment.

For a given ΔK_I, different materials exhibit different growth rates depending on such factors as atmosphere, temperature and cleanliness of the material. These factors must be considered when determining the growth rate as a function of ΔK_I.

The crack growth rate should be investigated over the range from a threshold stress intensity factor, K_{th} (no observable growth in a specified number of cycles), to a maximum stress intensity factor, K_c (rapid crack advance). With such crack growth data, it is possible to establish periodic inspection intervals to insure that the crack in question will not grow to the critical value before the next inspection.

Compliance

The surface inspection of crack length is often misleading because the surface trace of a growing crack is not an accurate representation of the sub-surface crack length. Therefore, a method of compliance can be used to find the actual crack length present in a material that is cycling within a ΔK_I range. In other words, the crack length, a, is a unique function of the applied load, P, and the crack opening displacement, C.O.D. Knowing this function for cracks whose lengths are carefully machined, it is possible to find the length of an existing fatigue crack by determining its load-C.O.D. record.

Summary

In view of the preceding named parameters, K_{Ic} and da/dN, it is possible to predict failure of a crack member via two different means. These are:

(1) The critical load to cause failure, P_c, may be estimated using the fracture toughness, K_{Ic}, and the known crack length, a.

(2) The critical crack length, a_c, may be estimated knowing the load, P, and the value of K_{Ic}. The rate at which the subcritical crack length approaches a_c may be estimated using the da/dN data.

Regardless of whether the load or crack length is increasing, the value of K_I is approaching the value of K_{Ic} and the life of the part is diminishing. Hopefully, catastrophic fracture will not occur while the part is in service because the fracture mechanic technology, if used correctly, will determine reliable intervals for inspection and recommend a safe service life for the part.

SPECIMENS AND EQUIPMENT

One-inch compact specimens, shown in Fig. 1, were used throughout the investigation. The specimen material was A27 cast steel with the composition, shown in Table 1. Heat treatment and simple mechanical properties are shown in Table 1.

Testing was conducted on a closed loop, servo-controlled machine. Crack opening displacements were measured using a fracture mechanics clip gage, and load was measured using a 20 kip load cell in series with the specimen.

All testing for fracture toughness was done according to the standard ASTM E399-72 [1] (Appendix B). In cases where the conditions of standard K_{Ic} testing could not be met, the J-integral method was employed and procedures similar to those outlined in Appendix A were followed.

DISCUSSION AND CONCLUSIONS

Fracture Toughness

The plane-strain fracture toughness versus temperature is shown in Fig. 2 and photographs of fracture surfaces are shown in Fig. 3. The upper shelf value is approximately 260 ksi$\sqrt{in}$, and the lower shelf is 40 ksi$\sqrt{in}$. The transition temperature occurred within the range of -50°F and +50°F.

Examining the toughness data in Fig. 2, it can be seen that the toughness values at temperatures above 100°F are high and the material may be considered to have high ductility in this range. On the other hand, at sub-zero temperatures, the toughness values are low and the material is highly brittle. It is this brittleness that can initiate a catastrophic failure, during a service condition, if the value of K_I reaches the value of K_{Ic} for the service temperature. Furthermore, if the service situation calls for operation over a large temperature range, an inspection should be made prior to the drop in temperature. The reason for this is that a value of K_I may not be critical at a higher temperature but may become critical as temperature drops, leading to catastrophic failure.

The toughness in the transition temperature range (-50°F to +50°F) is not precisely defined due to a large amount of scatter in this range. A user must exercise caution in picking a reliable toughness value for operation in this temperature range. A liberal estimate of toughness in this temperature range could lead to catastrophic failure if the temperature is decreased slightly more than expected. Consequently, it is advisable to be conservative while choosing a toughness value for operation in the transition range.

Crack Growth

The results of fatigue crack growth studies are presented in Fig. 4. The relation between crack growth and the range in stress intensity factor is

$$\frac{da}{dN} = C_o \, \Delta K^m \qquad \text{(4 restated)}$$

The values of the material constants C_o and m were found to be

$$C_o = 1.31 \times 10^{-11}$$

and

$$m = 3.8$$

for room temperature and neutral environmental test conditions.

In recent work by Barsom [7], the material constants for ferritic-pearlitic steels were reported to be $C_o = 3.6 \times 10^{-10}$ and $m = 3$. It should be noted that the crack growth rate for A27 cast steels is more dependent on the stress intensity range as indicated by the higher exponent, 3.8. However, for stress intensities below 30 ksi$\sqrt{in}$ the crack growth rate is lower due to the reduction in C_o for cast steel.

Compliance

A plot of load versus crack opening displacement (C.O.D.) for incremental, machined crack lengths is shown in Fig. 5. The slope, M, of the linear portion of the load-C.O.D. record is plotted versus crack length, a_N, in Fig. 6. The crack length obtained knowing a specific load-C.O.D. slope, M, is representative of the mean crack length of a bowed crack, which is commonly the case found in fatigue growth situations. Since ASTM E399-72 has a unique method of measuring crack length, a correction factor is necessary to adjust the "compliance mean crack length" to agree with the ASTM E399-72 crack length." This factor may be developed as follows:

The ASTM E399-72 crack length is defined as

$$a_{399} = \ell + \left(\frac{h_2 + h_3 + h_4}{3}\right) \tag{5}$$

where ℓ and h_N are illustrated in Fig. 7.

The compliance crack length may be defined as

$$a_{CCL} = \ell + \left(\frac{h_1 + h_2 + h_3 + h_4 + h_5}{5}\right) \tag{6a}$$

or

$$a_{CCL} = \ell + \left(\frac{h_2 + h_3 + h_4}{5}\right) \tag{6b}$$

or

$$a_{CCL} = \ell + \frac{3}{5}\left(\frac{h_2 + h_3 + h_4}{3}\right) \tag{6c}$$

ASTM specifies that $\ell = C_1\ a_{399}$ where $0.9 \leq C_1 \leq 1$. Substituting into Eq. 5, one obtains

$$\left(\frac{h_2 + h_3 + h_4}{3}\right) = a_{399} - C_1\ a_{399} = (1 - C_1)a_{399} \tag{7}$$

Equation 6c may now be written as follows:

$$a_{CCL} = C_1\ a_{399} + \frac{3}{5}\left(1 - C_1\right)a_{399} \tag{8a}$$

or

$$a_{CCL} = \left(\frac{2}{5}C_1 + \frac{3}{5}\right)a_{399} \tag{8b}$$

Using the ASTM specification that $0.9 \leq C_1 \leq 1$, Eq. 8b becomes

$$1.0 \leq \frac{a_{399}}{a_{CCL}} \leq 1.041 \tag{9}$$

or

$$a_{CCL} \leq a_{399} \leq 1.041a_{CCL} \tag{10}$$

Since cracks tend to bow a significant amount during fatigue cracking, the higher end of the range in Eq. 10 above will yield an accurate result. Therefore, it may be stated that the factor of 1.04 will adjust the compliance crack length (a_{CCL}) to the standard (a_{399}) crack length, i.e.

$$a_{399} = 1.04(a_{CCL}) \tag{11}$$

Once the load-C.O.D. slope is known, the length of the fatigue crack present may be determined. It should be noted, however, that the load-C.O.D. record for a fatigue cracked specimen will not pass linearly through the origin (Fig. 8) and, consequently, the user must take care in measuring the slope. The slope, M, should be measured in the form where

$$M = \frac{P_2 - P_1}{\Delta_2 - \Delta_1} \tag{12}$$

P_1, P_2 = loads above the minimum fatigue cracking load and within the linear elastic region

Δ_1, Δ_2 = crack opening displacements corresponding to P_1 and P_2

and <u>not</u> in the form $M = P_N/\Delta_N$, ($P_1 = \Delta_1 = 0$).

There are several reasons why the load-C.O.D. plot for a fatigue cracked specimen does not pass linearly through zero. The most popular of these may be the proposal that "crack closure" occurs upon total unloading. This produces an effective crack length which is shorter than the fatigue crack present and, consequently, the unloading line exhibits a higher slope.

Summary

(1) The fracture toughness of A27 cast steel has upper and lower shelf values of 270 ksi$\sqrt{\text{in}}$ and 40 ksi$\sqrt{\text{in}}$, respectively.

The upper shelf occurs above 100°F and the lower shelf occurs below -100°F.

(2) The A27 cast steel exhibited a fatigue crack growth rate which can be described by the equation

$$\frac{da}{dN} = 1.67 \times 10^{-11} \Delta K^{3.8} \qquad \text{(4 restated)}$$

(3) The "compliance" method for measuring crack lengths exhibited accurate results, provided the slopes of the load displacement lines are measured as

$$M = \frac{P_2 - P_1}{\Delta_2 - \Delta_1} \qquad \text{(12 restated)}$$

where P_1, P_2 $\equiv$ loads above the minimum fatigue cracking load and within the linear elastic region

Δ_1, Δ_2 $\equiv$ crack opening displacements corresponding to the loads P_1, P_2, respectively.

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APPENDIX A

SINGLE SPECIMEN FORMULA FOR DETERMINING J_{Ic}

Rice [2] has proposed a method by which J can be determined from a single specimen test. The intent of this appendix is to review his results and correlate J_{Ic} to other fracture toughness parameters such as K_{Ic} and G_{Ic}.

Deeply Cracked Specimens

In Rice's technique a compact tension specimen with a deep crack ($B/b \geq 1.25$) is loaded to the displacement of interest and J is determined from the expression

$$J = \frac{2}{bB} \int_0^{\Delta} P d\Delta \qquad \text{(A-1)}$$

where P = load in pounds

Δ = load line deflection of interest (in)

For compact specimens this expression reduces to

$$J = \frac{2A}{bB} \qquad \text{(A-2)}$$

where A = area under $P - \Delta$ curve

B = specimen thickness (in)

b = remaining ligament length (in)

Critical values of J are labeled as J_{Ic} and the integral is evaluated when crack extension is first encountered. The deflection of interest (Δ) for determining the critical J value has never been precisely defined. Consequently, various values of Δ have been considered. These are listed as follows:

(a) deflection of interest (Δ) exists at the first load drop in the load deflection record;

(b) deflection of interest (Δ) exists at first measurable crack extension;

(c) deflection of interest (Δ) exists at specimen separation.

In recent work by Clarke [8] the analysis which used the first load drop (a) seemed to be the more accurate for determining J_{Ic} value for a single specimen test.

J_{Ic} becomes equal to the critical strain energy release rate G_{Ic} for plane strain linear elastic behavior. J_{Ic} and G_{Ic} are related to plane strain fracture toughness, K_{Ic} by

$$J_{Ic} = G_{Ic} = \left(\frac{1 - \nu^2}{E}\right) K_{Ic}^2 \qquad \text{(A-3)}$$

or

$$K_{Ic} = \sqrt{\frac{J_{Ic}\,E}{1 - \nu^2}}$$

where E = Young's modulus

ν = Poisson's ratio

Equation (A-3) provides a check on the integrity of J_{Ic} numbers under elastic-plastic or fully plastic conditions. These values of J_{Ic} are consistent with K_{Ic} numbers [3,4,5] measured under linear elastic conditions as given by ASTM standard E399-72 [1].

APPENDIX B

VALIDITY OF FRACTURE TOUGHNESS TESTING

The definition of a mechanical property implies that a single number can be used to characterize a feature of mechanical behavior. Further, it implies that the property may be measured in a reproducible manner by different individuals. It would be desirable to have a high degree of standardization and reproducibility for all fracture properties.

In the USA, K_{Ic} was selected by ASTM as the property which was sufficiently characterized to evolve an acceptable standard test method. In this appendix a number of the considerations are reviewed and variables that must be taken into account in developing a standard test method are considered. Some of the most important variables are:

1. specimen size requirements, both crack length, a_0, and thickness, B;
2. crack sharpness requirements including prior strain history of the crack tip region;
3. detection of the onset of crack extension and the separation of crack extension from crack tip plastic deformation.

ASTM recognizes that if K_{Ic} is to be considered a material property, it must be independent of the variables mentioned above. In view of the analysis presented here, ASTM has developed a standard for fracture toughness testing which has been outlined as follows:

<u>Fatigue Cracking</u>

The first requirement governs the fatigue cracking test procedures. The first condition is:

$$K_{f(max)} \leq 0.6\ K_Q \qquad \text{and} \qquad \frac{K_{f(max)}}{E} \leq 0.002\sqrt{in} \tag{B-1}$$

where

$K_{f(max)}$ = maximum fatigue cracking stress intensity factor

K_Q = tentative value of fracture toughness

E = Young's modulus

This condition assures that the plastic zone size of fatigue cracking is much less than the plastic zone size at fast fracture. Also, it assures that the fatigue crack is in stable growth during fatigue cracking.

The second condition is:

$$0.6\left(\frac{\sigma_{y_{T_1}}}{\sigma_{y_{T_2}}}\right) K_Q \leq K_{f(max)} \tag{B-2}$$

where $\sigma_{y_{T_1}}$ = yield strength at fatigue cracking temperature T_1

$\sigma_{y_{T_2}}$ = yield strength at toughness test temperature T_2

This assures the same as the above except it takes into account the change in yield strength due to fatigue cracking and toughness testing being done at different temperatures.

The final three conditions are related to the toughness test. The first of these is:

$$\frac{P_{max}}{P_Q} \leq 1.10 \tag{B-3}$$

where P_{max} = maximum load

P_Q = 95% elastic line intercept load

This condition assures linear elastic behavior during the toughness test.

The third condition is:

$$a \quad 2.5\left(\frac{K_Q}{\sigma_y}\right)^2 < B \tag{B-4}$$

where σ_y = yield strength at the test temperature

B = sample thickness

a = crack length

This requirement assures that measured values of K_a is independent of sample geometry.

The last of these conditons is:

$$\frac{a_{sur}}{a_{399}} \geq 0.90 \tag{B-5}$$

where a_{sur} = surface crack excursion

a_{399} = crack length measured by ASTM standard

This assures that the measured crack length may be accurately used for stress intensity calculations without errors resulting from a large degree of crack front curvature.

Finally if all the above conditions are satisfied the tentative value, K_Q, becomes the value K_{Ic} (plane strain fracture toughness).

TABLE 1

COMPOSITION, CONDITION AND MONOTONIC PROPERTIES FOR A27 CAST STEEL (ASTM A27-65-35)

Composition

	C	S	Mn	Cr	Si	Ni	P	Mo	Al
w/o	0.18	0.010	0.82	0.08	0.44	0.03	0.019	0.02	0.04

Balance is F_e

Condition

Normalized and tempered to BHN 135 $\pm$ 5

Monotonic Properties

Elastic modulus, E, ksi - 28,500

Ultimate strength, S_u, ksi - 70

Yield strength, σ_y, ksi - 40

Hardness: 135 $\pm$ 5 BHN

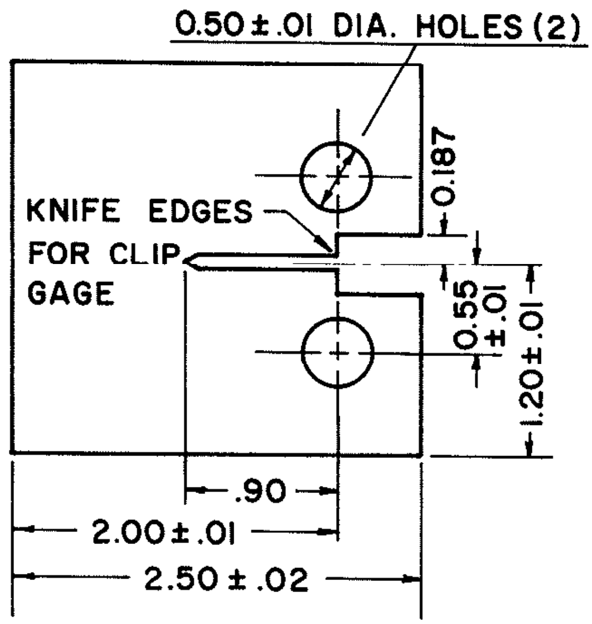

Fig. 1 Compact Specimen (1 inch thick)

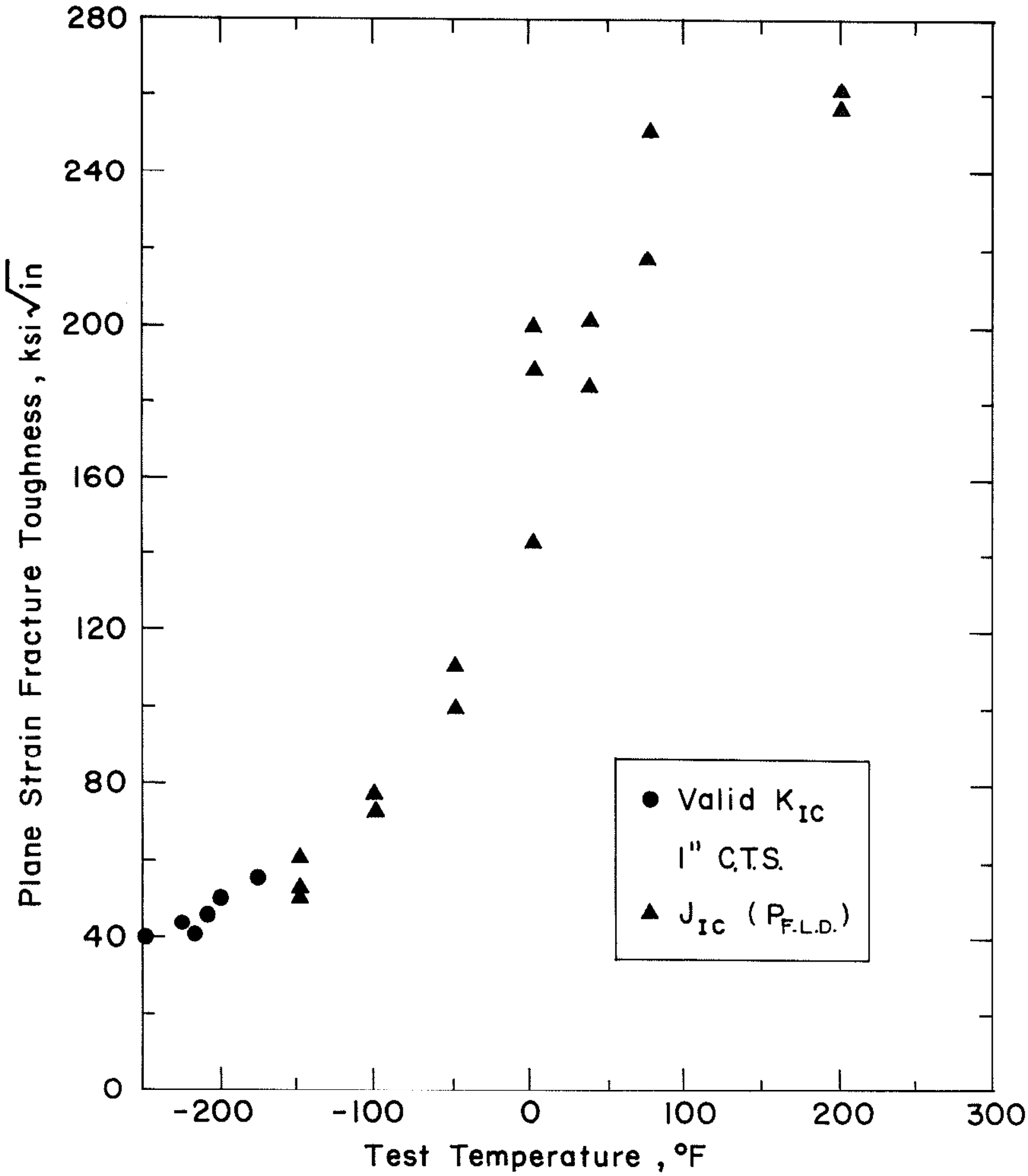

Fig. 2 Fracture Toughness versus Test Temperature for A27 Cast Steel

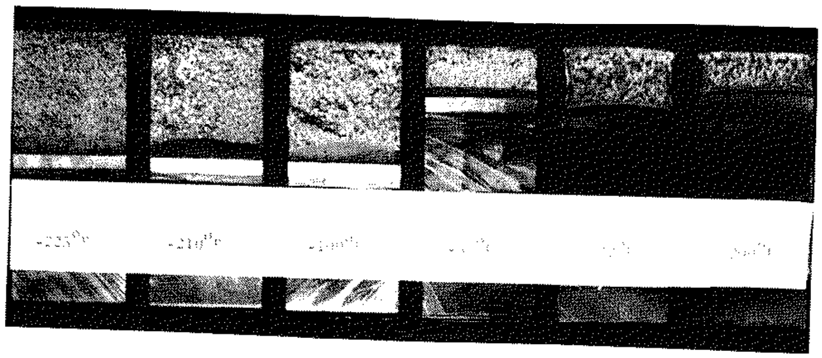

Fig. 3 Fracture Surface Photographs for 1 in. C.T.S.

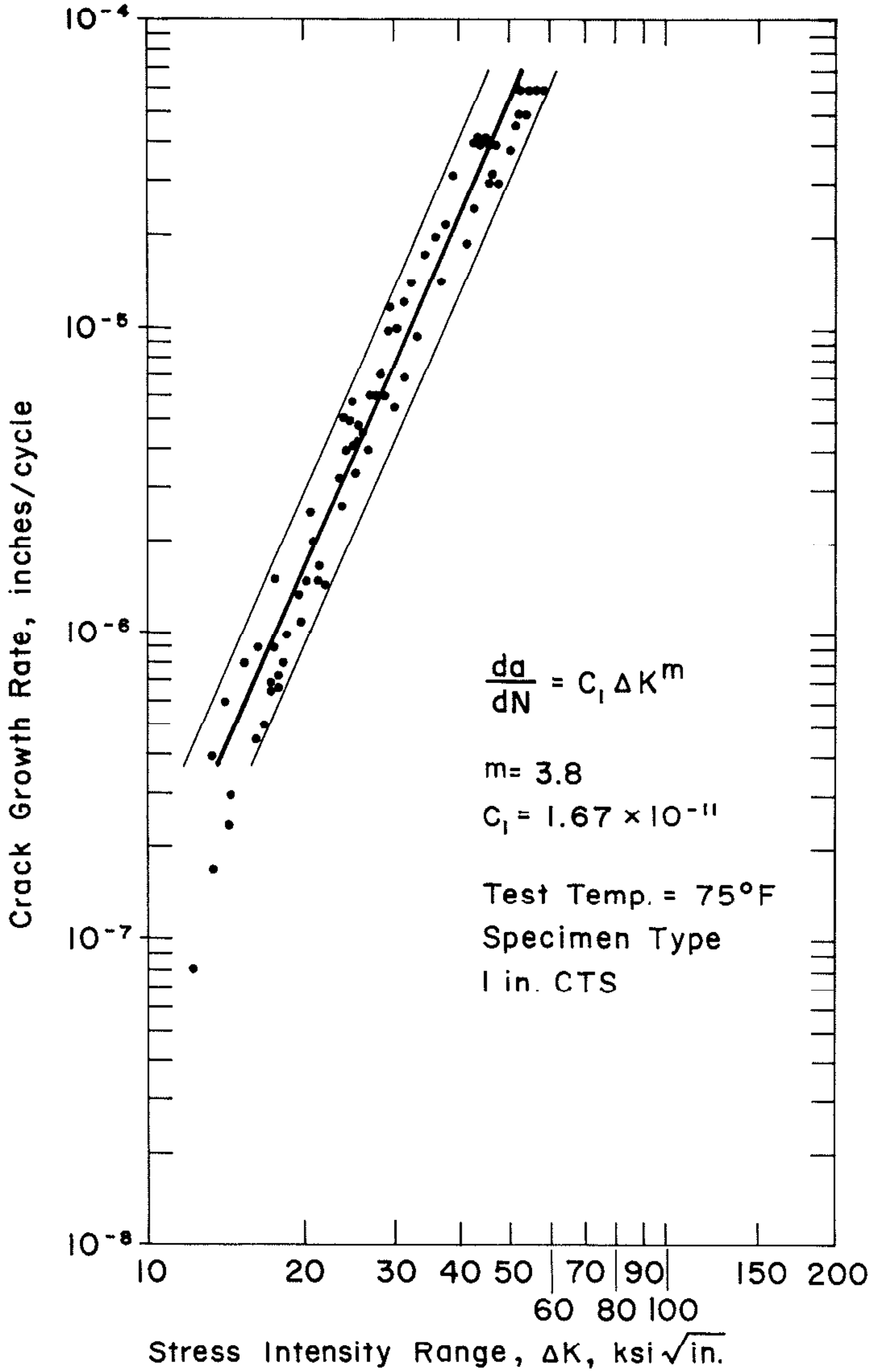

Fig. 4 Fatigue Crack Growth Rate for A27 Cast Steel

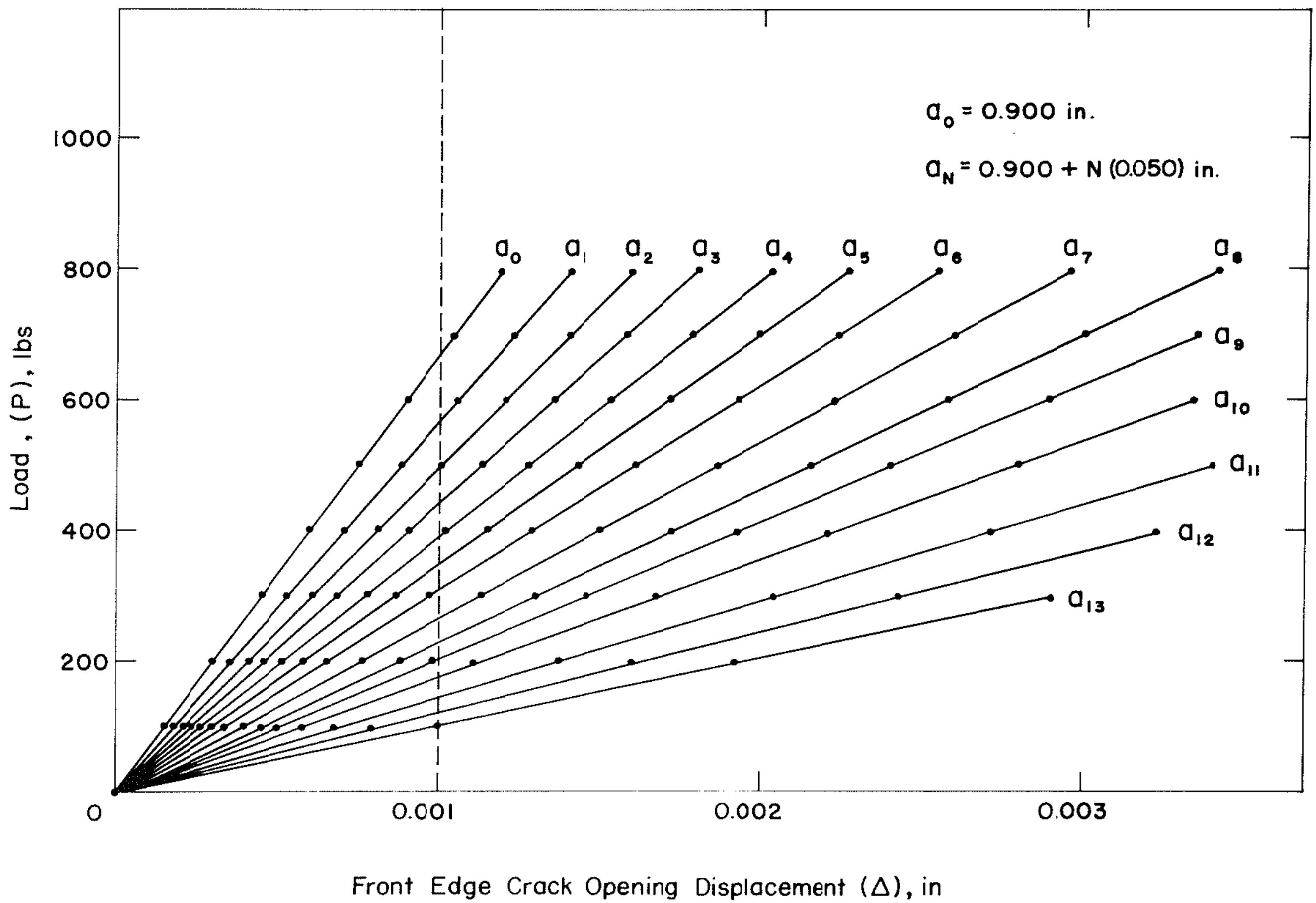

Fig. 5 Load-C.O.D. for Various Crack Lengths

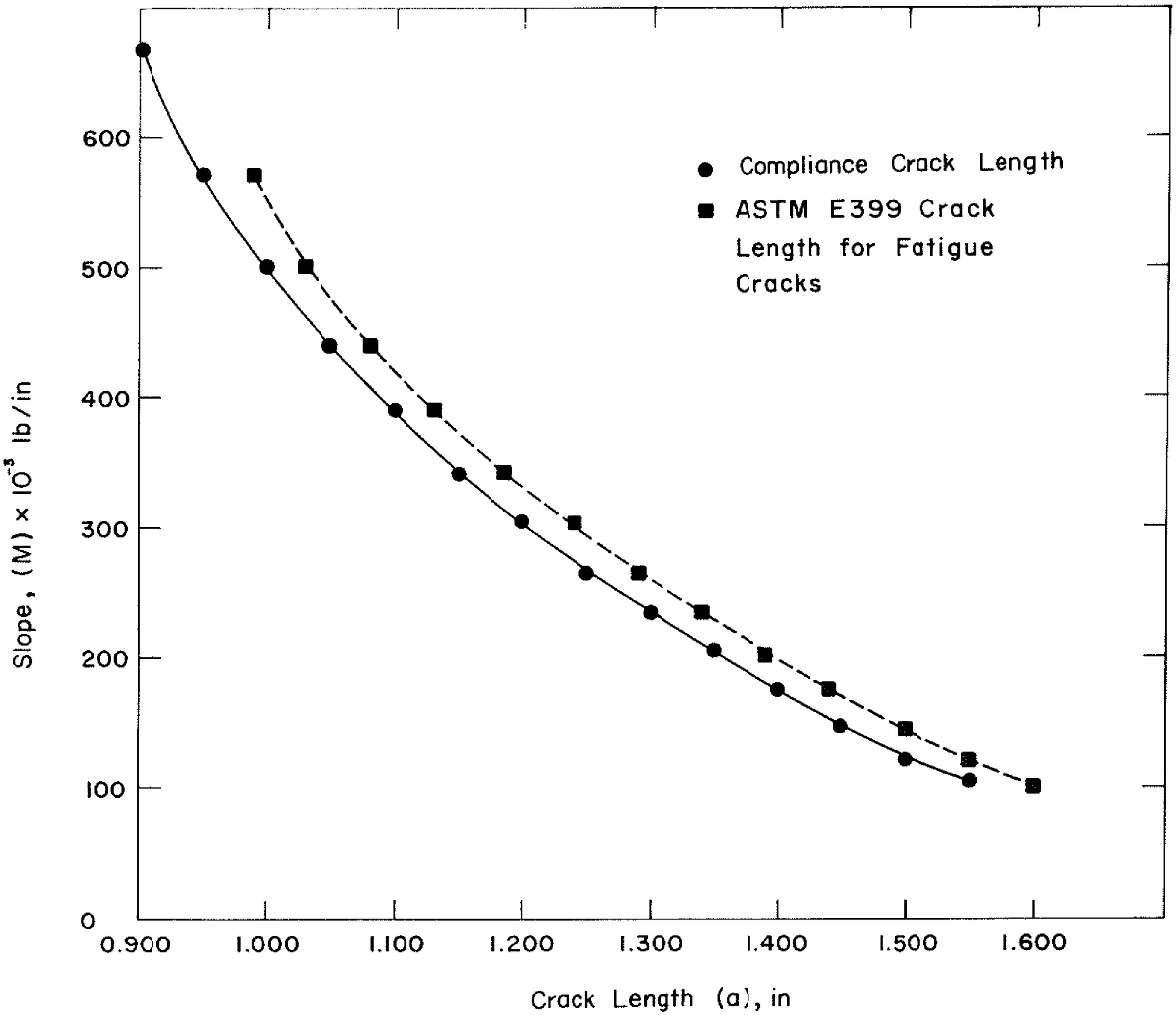

Fig. 6 Compliance Curve for Cast Steel 1 in. C.T.S.

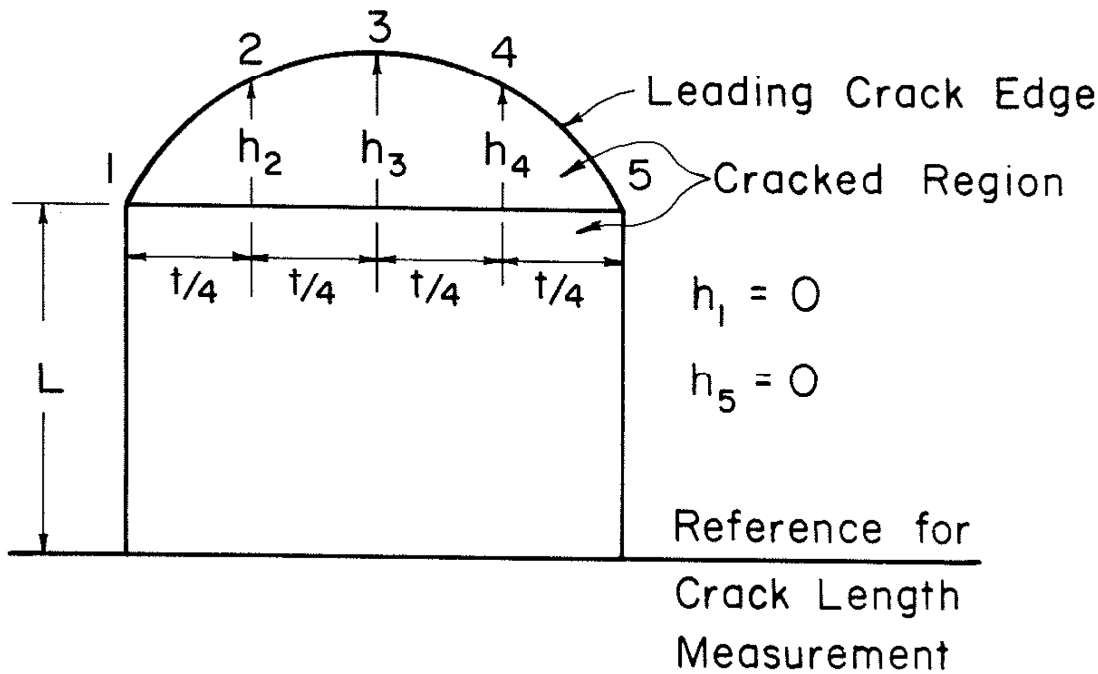

Fig. 7 Parameters for Crack Length Measurement

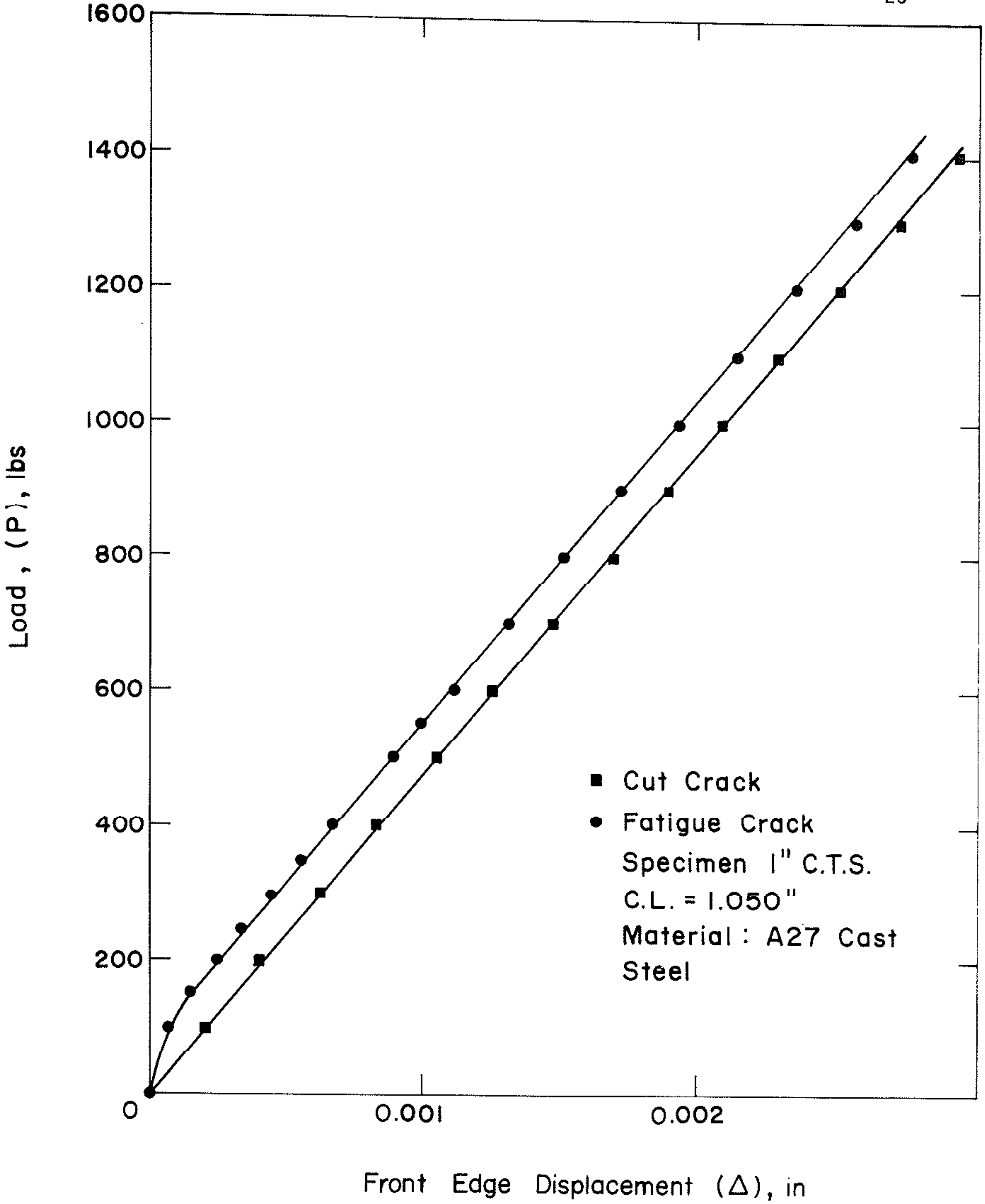

Fig. 8 Load - Displacement for Typical Crack