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Indian Standard

METHOD FOR PLANE STRAIN FRACTURE TOUGHNESS TESTING OF METALS

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INDIAN STANDARDS INSTITUTION
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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METHOD FOR PLANE STRAIN FRACTURE TOUGHNESS TESTING OF METALS

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Indian Standard

METHOD FOR PLANE STRAIN FRACTURE TOUGHNESS TESTING OF METALS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 12 April 1982, after the draft finalized by the Methods of Physical Tests Sectional Committee had been approved by the Structural and Metals Division Council.

0.2 The use of linear fracture mechanics is recently being applied to many design problems to give a fracture-safe structure containing a given defect size. Essentially the technique involves a study of the stresses and strains at the tips of sharp cracks or defects and relates them to the applied loading. The critical value of the stress intensity factor necessary for crack growth under a static load is called the fracture toughness (K_C). This approaches a minimum value K_{IC} under plain strain conditions (high triaxiality and restraint in thick sections) and becomes a material property in the same sense as proof stress.

0.3 The plane strain fracture toughness of a material is a property indicative of the resistance of that material to crack growth under conditions where the state of stress at the crack tip is predominantly triaxial and where plastic deformation is limited. In the test method specified in this standard, two stages are involved.

a) The development of a crack, and

b) The propagation of that crack under applied forces to produce fracture.

0.4 Unlike most other types of mechanical testing, plane strain fracture toughness testing is unusual in that there is no advance assurance that a valid K_{IC} will be determined in a particular type of test. The test has to be completed and the results analysed before it may be ascertained whether or not a valid measurement has been made. A validity check list has, therefore, been incorporated in this standard.

0.5 This standard has been formulated for ascertaining the effects of metallurgical variables, heat treatment and welding in quantitative terms significant to service conditions and for use as a basis for establishing design data.

0.6 In the preparation of this standard, assistance has been derived from the following publications:

ASTM E399-1974 Standard method of test for plane strain toughness testing of metallic materials. American Society for Testing and Materials.

DD 3-1971 Methods for plane strain fracture toughness testing. British Standards Institution.

0.7 In reporting the result of a test made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960*.

1. SCOPE

1.1 This standard prescribes the method of determining the plane strain fracture toughness (K_{IC}) of metals by bend or tension test of a single edge notched, test piece of at least 6·5 mm thickness.

2. PRINCIPLE OF TEST

2.1 The test consists in submitting a straight rectangular notched test piece, which has been precracked in fatigue, to either tension or a three point bending.

2.2 Autographic recording of the load versus displacement across the notch is recorded. The load corresponding to a 2 percent increment of crack extension is established by a specified deviation from the linear portion of the record. This load is used for determining K_{IC} by means of equations arrived at by stress analysis under plane strain conditions.

2.3 The fatigue crack should establish a sharp-crack condition, and for that reason the stress intensity level to generate the crack is limited to a relatively low value.

3. TERMINOLOGY

3.0 For the purpose of this standard, the following definitions shall apply.

*Rules for rounding off numerical values (*revised*).

3.1 Stress Intensity Factor (K_I) — It is a measure of the stress-field intensity near the tip of an ideal crack in a linear elastic medium when deformed so that the crack faces are displaced apart, normal to the crack plane. It is directly proportional to applied load and depends on specimen geometry.

3.2 Plane Strain Fracture Toughness (K_{IC}) — It is defined as the resistance to crack propagation in the presence of a notch and may be described in terms of static critical stress intensity factor under conditions of plane strain.

3.2.1 In the test methods specified in this standard, the lowest load, at which significant measurable extent of crack occurs, is used as a measure for K_{IC}. The load for significant measurable extension may correspond to the maximum load but usually the specimen will sustain a higher load than this (*see* Fig. 6).

4. REFERENCE SYMBOL

4.1 The following reference symbols have been used in the standard:

Symbol	*Descriptoin*
J	Notch length
a	Crack length, (that is notch length plus fatigue crack length)
b	Thickness of the specimen
W	Width of specimen
n	Notch width
K_{IC}	Fracture toughness under plane strain
σYS	Yield stress (0·2 percent proof stress)
K_F	Stress intensity of fatigue cycle
K_Q	K calibration to conform K_{IC}
P_Q	Load at which crack propagation starts
R_b, R_t	Specimen strength ratio in bending and tension respectively.

5. TEST PIECE

5.1 For valid results specimen thickness b and the crack length a, shall be not less than $2.5 \left(K_{IC}/\sigma YS \right)^2$

and $a \approx b$

5.2 If ligament size ($W - a$) is too small then the stress free boundaries interfere with the crack-tip stress field. Therefore, ($W - a$) shall be approximately equal to crack length a.

5.3 The length of fatigue crack shall be not less than 5 percent of length, a, and also not less than 1·25 mm.

5.4 Notch width n shall be not greater than 1/16 W, and the notch root radius shall be 0·12 mm *Max.*

Maximum apex angle of the notch including the crack shall be 30° (*see* Fig. 9).

5.5 Peak stresses (K_f) in fatigue pre-cracking shall be appreciably less than those in final toughness test:

K_f always $\leqslant$ 0·75 K_{IC} and K_f < 0·67 K_{IC} during last 1·25 mm (that is 2·5 percent W) of fatigue crack growth.

The crack shall be of uniform length across the section and not twisted or tilted.

5.6 The proportional dimensions and tolerances for the bend test pieces are given in Fig. 1 and tolerance for a range of tensile test pieces having thicknesses from 13 mm to 100 are given in Fig. 2.

5.7 Overall length for both specimens shall be approximately equal to 5 W. For bend test specimen, span length shall be not less than 4 W.

6. TEST PROCEDURE

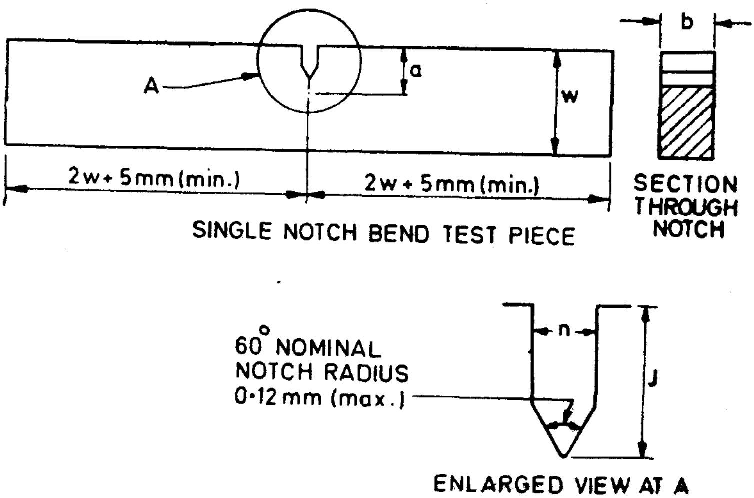
6.1 The notched, precracked in fatigue specimen, is tested by bend or tension test. Autographic recording of load against displacement is recorded. Testing may be performed in any machine suitable to provide the load for bending or tension and also capable of facilitating autographic recording.

6.2 Bend Test Fixture — Fixture for bend test shall be designed so as to minimize friction between the specimen and the supports. A recommended fixture design is provided in Fig. 3. Low tension springs (like rubber bands) hold the supporting rolls quite firmly and allow limited motion along plane surfaces.

6.3 Grips and Fixtures for Single Edge Notched Tension Test — Figure 4 shows the gripping arrangement for tension testing specimen. To allow rotation of the specimen when loaded, the clevis and pin arrangement is employed both at the top and the bottom.

6.4 Load shall be measured by conventional load cell.

6.4.1 The specimen shall be loaded at such a rate that the rate of increase of stress intensity is within the range 0·55 to 2·75 MPa m^{3}/s corresponding to loading rate for this standard 25 mm thick specimen between 0·34 to 1·7 KN/s.



Test piece proportion, dimensions and limits

Width		=	W
Thickness		=	$b = \frac{1}{2} W$
Crack length	a	=	0·45 W to 0·55 W
Notch length	j	=	0·25 W to 0·45 W
that is 0·25 W When	W	=	13 mm
0·45 W When	W	=	150 mm

Notch width not greater than 1/16 W (when W is equal to or less than 25 mm, n may be up to $1\frac{1}{2}$ mm). Faces parallel and perpendicular to 0·02 mm taper per 10 mm run.

FIG. 1 STANDARD BEND TEST PIECE

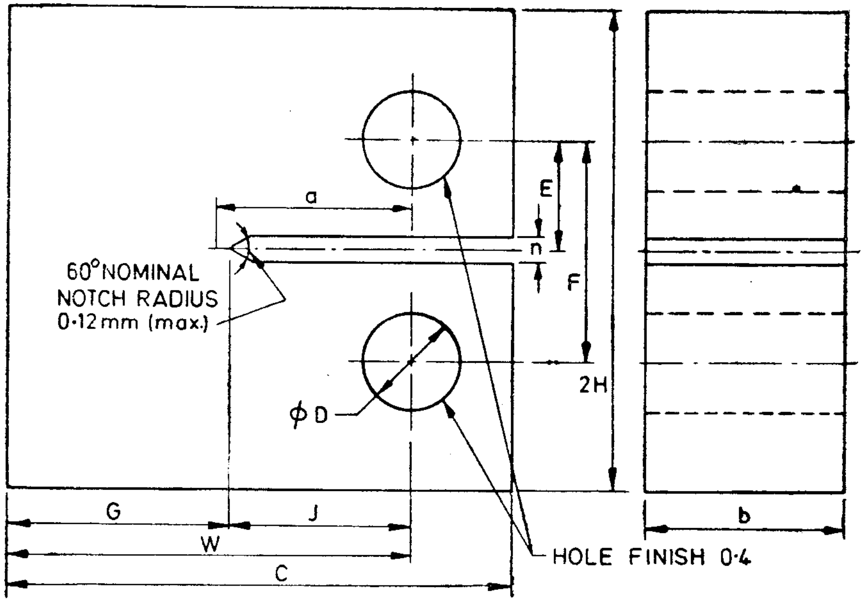
6.5 Displacement across notch opening shall be measured by clip gauge (*see* Fig. 5) whose output shall be linear.

6.6 The load-displacement relationship shall be recorded on an autographic recorder with the initial slope of the plot between 40 and 65°.

7. CALCULATION AND INTERPRETATION OF RESULTS

7.1 Load to Produce Crack

7.1.1 For calculation use maximum load (P_Q) if response is linear to fracture (*see* Fig. 6a).



Proportional dimensions and limits

Net width	*W*	=	± 0·005 *W*
Crack length	*a*	=	0·45 *W* to 0·55 *W*
Thickness	*b*	=	0·5 *W* + 0·010 *W*
Total width	*c*	=	1·25 *W* + 0·01 *W*
Hole diameter	*D*	=	0·25 *W* + 0·005 *W*
Half hole centres	*E*	=	0·275 *W* + 0·005 *W*
Hole centres	*F*	=	0·55 *W*
	G	=	not less than 0·55 *W*
	H	=	0·6 *W* ± 0·005
	J	=	*see* Fig. 4
Notch width	*n*	=	not greater than 1/16 *W*

NOTE — When *W* is equal to or less than 25 mm, *n* may be up to 1½ mm. Surface parallel and perpendicular as applicable to 0·02 mm taper/10 mm run.

	Size	*b*	*W*	*C*	*a Max*	*n Max*	*E*	*F*	*H*	*D*	*G Min*
	13	13	26	32·5	14·5	1·5	7·2	14·3	15·6	6·5	14·3
	25	25	50	62·5	27·5	3·1	13·8	27·5	30	12·5	27·5
Hence:	50	50	100	125	55	6·3	27·5	55	60	25	55
	75	75	150	188·5	82·5	9·4	41·3	82·5	90	37·5	82·5
	100	100	200	250	110	12·5	55	110	120	50	110

FIG. 2 STANDARD TENSION TEST PIECE

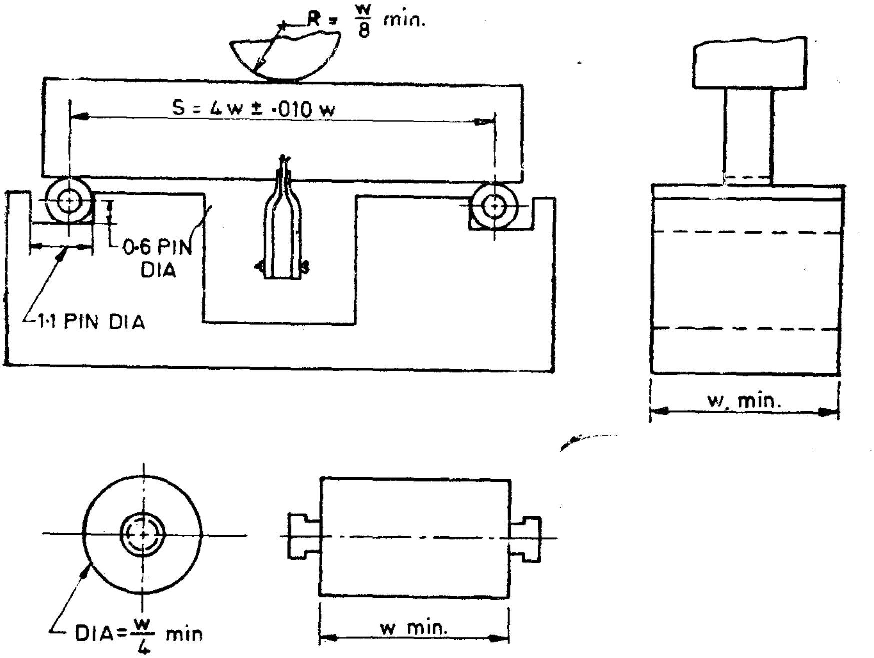


FIG. 3 BEND TEST FIXTURE DESIGN

7.1.2 'Pop-in' (rapid crack propagation producing displacement, or falling load) shall be used (P_Q) when it occurs unless preceded by curvature (Fig. 6b).

7.1.3 Plots showing curvature due to slow growth or local plasticity (Fig. 6c) use offset procedure (Fig. 7). In this case draw a second line 5 percent less slope (Fig. 7) then determine P_X and use any preceding $P > P_X$ as P_Q or determine ΔV_1 and compare with ΔV_2 at 0·8 P_X. If therefore, $\Delta V_2 < 0{\cdot}25\ \Delta V_1$ then $P_X = P_Q$.

7.2 For single edge notched tension test the value of K calibration,

$$K_Q = (P_Q/BW^{\frac{1}{2}}).f (a/W)$$

where

$$f (a/W) = \frac{\left(2 + \frac{a}{W} \right) 0{\cdot}886 + 4{\cdot}64 \frac{a}{W} - 13{\cdot}32 \frac{a^2}{W^2} + 14{\cdot}72 \frac{a^3}{W^3} - 5{\cdot}6 \frac{a^4}{W^4}}{\left(1 - \frac{a}{W} \right)^{3/2}}$$

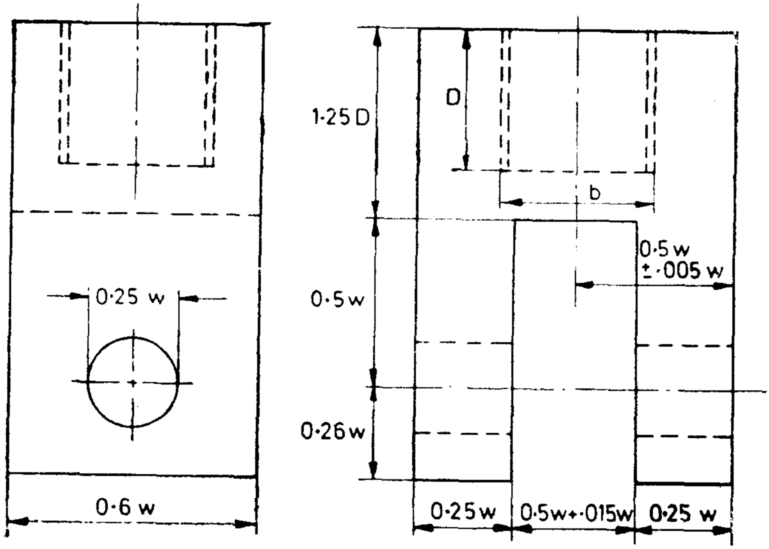


FIG. 4 TENSION TESTING CLEVIS

7.3 For single edge notch three point bend test the K calibration

$$K_Q = (P_Q S/BW^{3/2}) . f(a/W)$$

where

$$f(a/W) = \frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1{\cdot}99 - \left(\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)\left(2{\cdot}15 - 3{\cdot}93\frac{a}{W}\right) + 2{\cdot}7a^2W\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}}$$

7.4 P_Q obtained from **7.1**, is incorporated into the appropriate relationship of **7.2** and **7.3** and the K_Q values are obtained.

7.5 If K_Q value enables thickness, that is $b \geqslant \left(2{\cdot}5 \frac{K_Q^2}{\sigma YS} \right)$ and crack length criteria that is $a \geqslant (2{\cdot}5 \; K_Q/\sigma YS)^2$ to be met then $K_Q = K_{IC}$.

7.6 Specimen strength ratio for bend test is given by

$$Rb = 6 \; P_{max} . \; W/b \; (W - a)^2 \; \sigma YS$$

where P_{max} = maximum load the specimen can sustain.

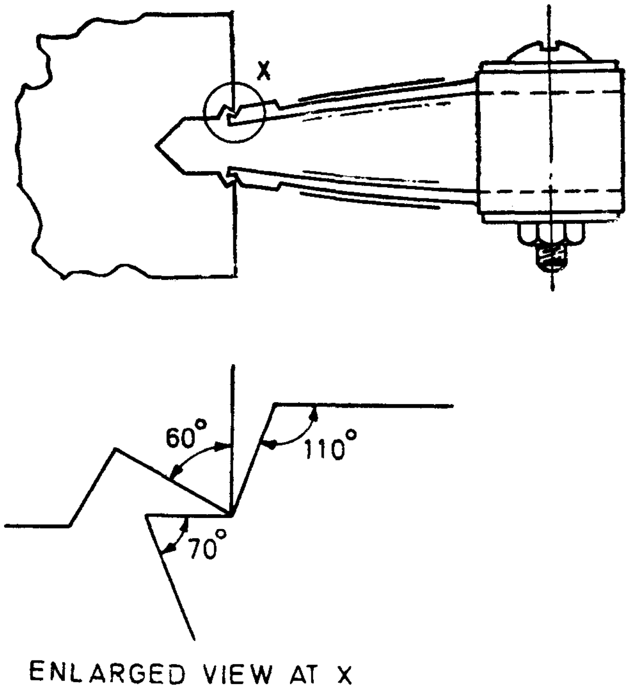


FIG. 5 ATTACHMENT OF GAUGE BETWEEN MACHINED KNIFE EDGES

7.7 For tension test, specimen strength ratio

$$R_t = 2\, P_{max}\, (\, 2W + a\,)/B\ (\, W - a\,)^2\ \sigma YS.$$

NOTE — R_b and R_t unlike K_{IC} are not a concept of linear elastic fracture mechanics. This gives a good comparison of toughness of material where the specimen size was not sufficient to given a valid K_{IC} value but the size was sufficient enough to provide the maximum load value for pronounced crack extension before the plastic instability stage.

8. REPORT

8.1 The report for the test piece shall consist of the following data:

a) Thickness — b in m
b) Width — W in m
c) Length — l in m (for bend test the half loading span to be reported)

d) Fatigue precracking conditions:

   1) Maximum fatigue stress intensity K_f, for final propagation of crack — $MN/m^{3/2}$

   2) The ratio K_f/K_{IC}

   3) Temperature of test piece at the time of preparing crack

   4) The R ratio value

e) Length of crack — a in m

f) 1) Temperature at the time of testing in °C

   2) Environmental condition that is humidity percent

g) Load/displacement record and association calculations

h) Yield strength (σYS) or 0·2 percent proof stress MN/m^2

j) The value of fracture toughness (K_{IC}) $MN/m^{3/2}$

k) Crack plane orientation and direction of propagation

m) Fracture appearance (*see* Fig. 8).

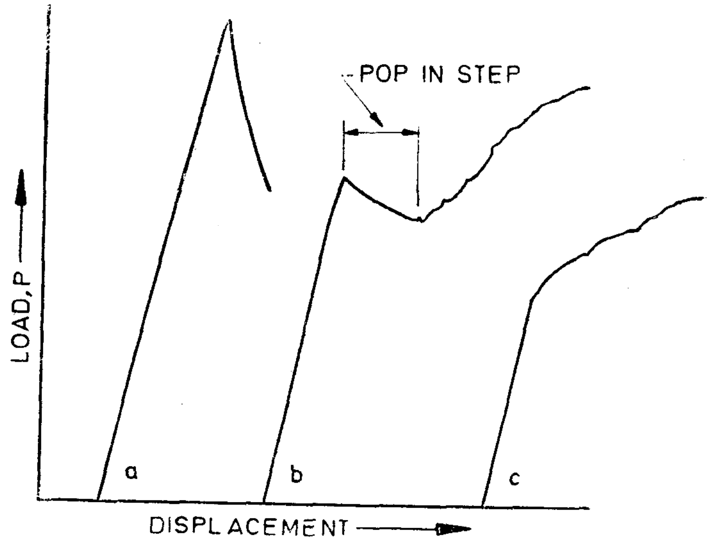


FIG. 6 SCHEMATIC LOAD DISPLACEMENT CURVES

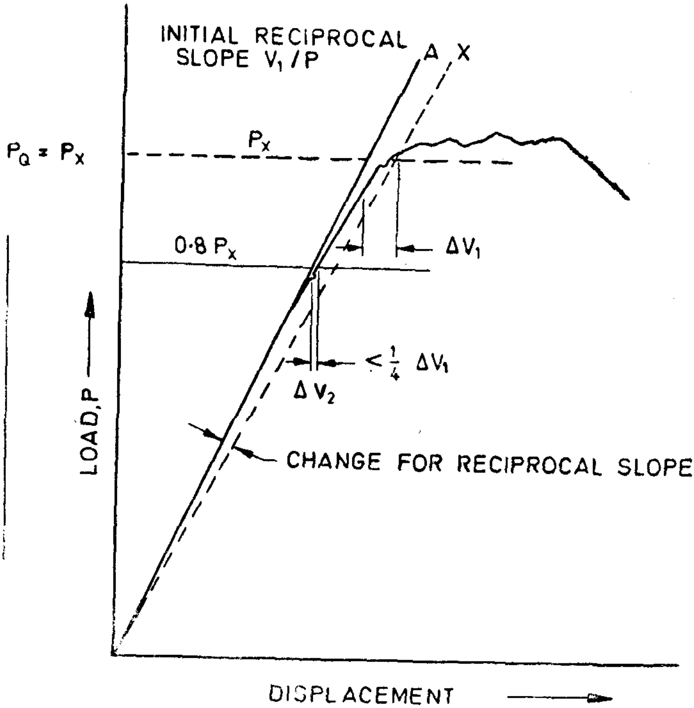


FIG. 7 TYPICAL LOAD DISPLACEMENT RECORD SHOWING QUANTITIES INVOLVED IN A PROCEDURE FOR LOAD DISPLACEMENT RECORD ANALYSIS

9. VALIDITY CHECK LIST

9.0 The following checks shall be carried out before proceeding to the next stage, to ensure that the test is valid at any stage during the testing procedure.

9.1 Stage A — Before fatigue crack, check that the test piece has been machined to the dimensions and tolerances as stated.

9.2 Stage B — Before fracture testing, check:

a) The minimum surface crack length shall be at least 0·425 W.

b) The fatigue crack shall extend for at least 1·25 mm or 2·5 percent W from the root of the machined notch, whichever is the greater.

c) The difference between the two surface crack length measurements shall be not greater than 5 percent *W*.

d) The plane of the crack shall lie in the plane of the notch within 5°.

e) The crack shall have been grown 1·25 mm or 2·5 percent *W* at the lower level of stress intensity.

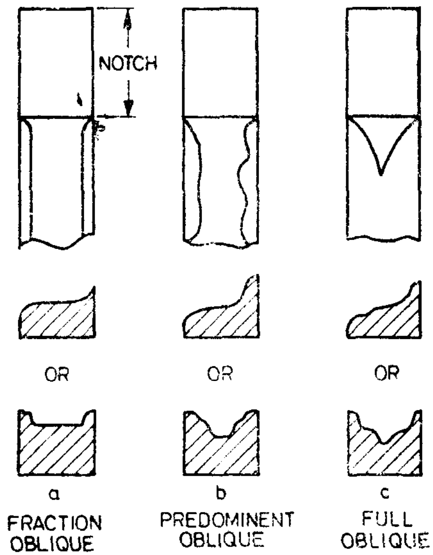


FIG. 8 FRACTURE APPEARANCE

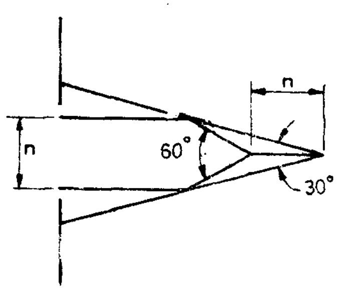


FIG. 9 NOTCH GEOMETRY

9.3 Stage C — After fracture testing:

a) multinucleation shall be not present on the tip of the fatigue crack.

b) the average of the three measurements of crack length shall be such that the a/W ratio is between 0·45 and 0·55.

c) no two of the three measurements of crack length shall differ by more than 2·5 percent W.

d) no two possible measurements of crack length shall differ by more than 5 percent W.

9.4 Stage D — Analysis of data is as follows:

a) The initial inclination of the force/displacement record shall be between 40° and 65°.

b) The deviation at 0·8 P_Q shall be less than one quarter of the deviation at P_Q (Type 1 records only).

9.5 Stage E — Calculation is as follows:

a) The thickness and the crack length shall exceed the factor $\frac{2 \cdot 5 (K_Q)^2}{(\sigma YS)}$

b) K_f shall not exceed 67 percent K_{IC} (or modified criterion for low temperature testing).

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Base Units

QUANTITY	UNIT	SYMBOL
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Supplementary Units

QUANTITY	UNIT	SYMBOL
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

QUANTITY	UNIT	SYMBOL	DEFINITION
Force	newton	N	1 N = 1 kg.m/s^2
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m
Frequency	hertz	Hz	1 Hz = 1 c/s (s^{-1})
Electric conductance	siemens	S	1 S = 1 A/V
Electromotive force	volt	V	1 V = 1 W/A
Pressure, stress	pascal	Pa	1 Pa = 1 N/m^2