BS 7448-1:1991

Incorporating
Amendment No. 1 and
Corrigendum No. 1

Fracture mechanics toughness tests —

Part 1: Method for determination of K_{Ic}, critical CTOD and critical J values of metallic materials

ICS 77.040.10

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Iron and Steel Standards Policy Committee (ISM/-) and the Non-ferrous Metals Standards Policy Committee (NFM/-) to Technical Committee ISM/NFM/4, upon which the following bodies were represented:

Aluminium Federation
British Gas plc
British Non-ferrous Metals Federation
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The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

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United Kingdom Atomic Energy Authority

This British Standard, having been prepared under the direction of the Iron and Steel and the Non-ferrous Metals Standards Policy Committees, was published under the authority of the Standards Board and comes into effect on 20 December 1991

The following BSI references relate to the work on this standard:
Committee reference ISM/NFM/4
Draft for comment 90/41825 DC

ISBN 0 580 20037 X

Amendments issued since publication

Amd. No.	Date	Comments
10543	August 1999	
12018 Corrigendum No. 1	27 February 2002	Corrections to Figure 10, Table 2 and **8.2**.

Contents

Foreword

This part of BS 7448 has been published under the direction of the Iron and Steel and the Non-ferrous Metals Standards Policy Committees.

It gives a method for determining plane strain fracture toughness (K_{Ic}), critical crack tip opening displacement (CTOD)[1] and critical J fracture toughness values for metallic materials under displacement controlled monotonic loading at quasistatic rates.

This part of BS 7448 combines and extends the methods for determining K_{Ic} values, given in BS 5447, and the method for determining crack opening displacement (COD), given in BS 5762:1979, BS 5447:1977 and BS 5762:1979 are withdrawn.

Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone are covered in BS EN ISO 12737. General determinations of fracture toughness, where the fracture behaviour determines the relevant fracture parameters (e.g. K_{Ic}, CTOD or J) are covered in the procedures in this part of BS 7448, BS 7448-2 and BS 7448-4.

The other three parts of BS 7448 are as follows:

- *— Part 2: Method for determination of K_{Ic}, critical CTOD or J values of welds in metallic materials;*
- *— Part 3: Method for determination of dynamic toughness[2];*
- *— Part 4: Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials.*

It has been assumed in the drafting of this standard that the execution of its provisions is entrusted to appropriately qualified and experienced people.

Safety note. It is important to note that tests of the type described involve the use of large forces, and may involve the rapid movement of machine parts and fractured test specimens. Therefore it is important to consider the safety of machine operators.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 40, an inside back cover and a back cover.

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[1] In this British Standard the term CTOD, which refers to crack tip opening displacement, is synonymous with the term COD in BS 5762.

[2] In preparation.

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1 Scope

This part of BS 7448 specifies a method for determining the opening mode plane strain fracture toughness (K_{Ic}), the critical crack tip opening displacement (CTOD) fracture toughness, and the critical J fracture toughness of metallic materials. The method uses fatigue precracked specimens. These are tested in displacement controlled monotonic loading at a constant rate of increase in stress intensity factor within the range 0.5 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ to 3.0 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ [3] during the initial elastic deformation. The specimens are loaded to fracture or the maximum force associated with plastic collapse. The method is especially appropriate to materials that exhibit a change from ductile to brittle behaviour with decreasing temperature. No other influences of environment are covered.

The definition of fracture toughness values relevant to particular structural integrity assessments is outside the scope of this British Standard.

NOTE 1 The titles of the publications referred to in this standard are listed on the inside back cover.

NOTE 2 Numbers in square brackets in the text refer to numbered items in the Bibliography in Appendix A.

NOTE 3 This British Standard does not cover the determination of K_{Ic} alone. Such determinations are covered in BS EN ISO 12737.

2 Definitions

For the purposes of this part of BS 7448 the following definitions apply.

2.1
stress intensity factor (K)
the magnitude of the stress field near the crack tip (a stress-field singularity) for a particular mode (see **2.2**) in a homogeneous, ideally linear-elastic body

NOTE It is a function of applied force, crack length and specimen geometry, and is expressed in units of $\text{MPa}\cdot\text{m}^{0.5}$.

2.2
opening mode
opening displacement of the surfaces of a crack in a direction normal to the original (undeformed) crack plane near the crack tip

2.3
plane strain fracture toughness (K_{Ic})
a measure of a material's resistance to crack extension when the stress state near the crack tip is predominantly plane strain, plastic deformation is limited, and opening mode monotonic loading is applied

2.4
maximum fatigue stress intensity factor (K_f)
the maximum value of opening mode stress intensity factor which is applied during the final stages of fatigue crack extension

2.5
crack tip opening displacement (CTOD)
the displacement of the surfaces of a crack normal to the original (undeformed) crack plane at the tip of the fatigue precrack, expressed in mm

2.6
critical CTOD
a value of CTOD associated with a particular type of crack extension (see clause **3**)

2.7
***J*-integral**
a mathematical expression for a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front [1], expressed in J/mm^2 [4]

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[3] $0.031\ 6\ \text{MPa}\cdot\text{m}^{0.5} = 1\ \text{N}\cdot\text{mm}^{-1.5} = 0.031\ 6\ \text{MN}\cdot\text{m}^{-1.5}$.

[4] $1\ \text{J/mm}^2 = 1\ \text{MJ/m}^2$.

2.8
J
an experimental equivalent of the J-integral

2.9
critical J
a value of J associated with a particular type of crack extension (see clause **3**)

2.10
brittle crack extension
an abrupt crack extension which occurs with or without prior stable crack extension (see **2.11**)

2.11
stable crack extension
slow stable crack extension that includes the stretch zone width (see **2.12**)

NOTE In true displacement control the crack extension usually stops when the applied displacement is held constant.

2.12
stretch zone width (SZW)
the length of crack extension that occurs during crack tip blunting; that is, prior to the onset of brittle crack extension, pop-in (see **2.13**) or slow stable crack extension, and which occurs in the same plane as the fatigue precrack

2.13
pop-in
a discontinuity in the force versus displacement record

NOTE The pop-in corresponds to a sudden increase in displacement, and, generally, a sudden decrease in force. Subsequently, the displacement and force increase relatively slowly to above their respective values at pop-in (see **9.1**).

3 Symbols and designations

For the purposes of this part of BS 7448 the following symbols and designations apply.

a	nominal crack length (see Figure 2 to Figure 6) *or,* for the purposes of fatigue precracking (see **6.4.5** and **6.4.6**), an assumed value $\leq a_o$
a_o	average original crack length (see **8.7.2**)
B	specimen thickness
C	total width of compact specimen
E	Young's modulus of elasticity at the temperature of interest
f	a mathematical function of $\left(\frac{a}{W}\right)$ or $\left(\frac{a_o}{W}\right)$ for bend specimens
f'	a mathematical function of $\left(\frac{a}{W}\right)$ or $\left(\frac{a_o}{W}\right)$ for compact specimens
F	applied force
F_d	particular value of F, as shown in Figure 15
F_c	applied force at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm
F_f	maximum fatigue precracking force during the final stages of fatigue crack extension (see **6.4.5** and **6.4.6**)
F_m	applied force at the first attainment of a maximum force plateau for fully plastic behaviour
F_{max}	maximum force in a K_{Ic} determination (see Figure 15)
F_Q	particular value of F, as shown in Figure 15
F_u	applied force at the onset of a brittle crack extension or pop-in when the event is preceded by Δa equal to or greater than 0.2 mm
J	experimental equivalent of the crack tip J-integral

J_c	critical J at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm
J_m	value of J at the first attainment of a maximum force plateau for fully plastic behaviour
J_u	critical J at the onset of brittle crack extension or pop-in when the event is preceded by Δa equal to or greater than 0.2 mm
K	stress intensity factor
$\dot{K}$	rate of change of K with time
K_Ic	plane strain fracture toughness
K_f	maximum fatigue stress intensity factor applied during the final stages of fatigue crack extension
K_Q	provisional value of K_Ic
q	displacement of bend specimen or stepped notch compact specimen along the load-line
q_c	value of q at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm
q_m	value of q at the first attainment of a maximum force plateau for fully plastic behaviour
q_p	plastic component of q corresponding to F_c, F_u and F_m
q_u	value of q at the onset of brittle crack extension or pop-in when the event is preceded by Δa equal to or greater than 0.2 mm
R	fatigue force ratio, i.e. the algebraic ratio of minimum to maximum fatigue precracking force during any single cycle of fatigue operation
S	span between outer loading points in three point bend test
T	test temperature
U_p	plastic component of area under plot of force (F) versus specimen displacement along the load-line (see Figure 17)
V	notch opening displacement at or near to notch mouth NOTE In a stepped notch compact specimen $V = q$.
V_c	value of V at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm
V_m	value of V at the first attainment of a maximum force plateau for fully plastic behaviour
V_p	plastic component of V corresponding to F_c, F_u and F_m (see Figure 16)
V_u	value of V at the onset of brittle crack extension or pop-in when this is preceded by Δa equal to or greater than 0.2 mm
W	effective width of test specimen
y	half the distance between knife edge fixing points, as shown in Figure 8 and Figure 9
z	distance of the notch opening gauge location above the surface of the specimen [see Figure 8(b)]
δ	crack tip opening displacement (CTOD)
δ_c	critical CTOD at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm
δ_m	value of CTOD at the first attainment of a maximum force plateau for fully plastic behaviour
δ_u	critical CTOD at the onset of brittle crack extension or pop-in when the event is preceded by Δa equal to or greater than 0.2 mm
Δa	average stable crack extension, including SZW (see **8.7.3**)
ΔK	difference between the maximum and minimum values of K during any single cycle of fatigue precracking
v	Poisson's ratio
σ_TSP	tensile strength at the temperature of fatigue precracking
σ_YS	0.2 % proof strength at the temperature of the fracture test[a]
σ_YSP	0.2 % proof strength at the temperature of fatigue precracking

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[a] At present no British Standard exists for the measurement of tensile properties below ambient temperature. In these cases the values to be used are subject to agreement between the parties concerned.

4 Principle

A fatigue crack is extended in a single edge notched bend or compact specimen by applying an alternating force within controlled limits. The specimen is then subjected to an increasing monotonic force. Measurements are made of the forces and displacements to the point when either brittle crack extension occurs or the specimen reaches a maximum force condition. The applied force is plotted against displacement to define this point on a curve. This is analysed, and when specified validity criteria are met, the point is used to determine a plane strain fracture toughness (K_{Ic}). When the validity criteria are not met, the point is used to determine either a critical CTOD fracture toughness, or a critical J fracture toughness, or both, depending on the choice of specimen design and displacement measurement, as indicated in Figure 1.

5 Test specimens

5.1 General

5.1.1 Each specimen shall be of one of the following designs (see **5.2**):

a) rectangular cross-section three point bend (see Figure 2);

b) square cross-section three point bend (see Figure 3);

c) straight notch compact (see Figure 4);

d) stepped notch compact (see Figure 5).

NOTE 1 If agreed by the parties concerned the following alternative width (W) to thickness (B) ratios may be used:

a) rectangular section bend specimens: $1.0 < W/B \leq 4.0$;

b) straight notch compact specimen (see Figure 4): $0.8 \leq W/B \leq 4.0$.

NOTE 2 Specimens having W/B ratios greater than 2 will have an increased tendency to buckle.

5.1.2 The test specimen shall have the dimension B equal to the full thickness of the material to be tested.

However, provided that they are reported (see clause **11**), test specimens having thicknesses less than the test material (sub-size and/or side grooved specimens) may be used in one or more of the following circumstances:

a) when a particular combination of specimen design, material and temperature has been demonstrated to give values of fracture toughness that are independent of specimen thickness;

NOTE 1 This circumstance may apply when the specimen has adequate thickness to give a valid K_{Ic} value (see **5.3** and Table 1).

b) when there is an established correlation for specimen thickness for the sub-size thickness tested;

c) when no value of thickness is given in a product specification. In this case the specimen dimension B shall be as large as possible.

NOTE 2 Sub-size and/or side grooved specimens may give values of fracture toughness that are different to those associated with full thickness specimens, and should be used with caution.

5.1.3 The notch profile shall be such that it is within the envelope shown in Figure 6. In order to expedite fatigue precracking the machined notches in the test specimens are normally produced by milling, sawing or disc grinding.

When a milled notch is used the notch root radius shall be not greater than 0.10 mm. When a sawn, disc ground or spark eroded notch is used, the notch tip shall have a width of not greater than 0.15 mm.

Because it is generally impractical to machine 0.15 mm wide notches to depths greater than 2.5 mm, it is allowable to machine a stepped width notch.

Alternatively, if fatigue crack initiation and/or propagation is difficult to control (see **6.4.7**), a chevron notch configuration as shown in Figure 7 may be used.

When a chevron notch is used, the root radius shall be not greater than 0.25 mm.

The plane of the notch shall be perpendicular to the specimen surfaces to within ±2°.

When required, knife edges shall be machined into the specimen or attached. They shall be one of the types shown in Figure 8 and Figure 9. The dimension $2x$ shall be within the working range of the notch opening displacement gauge. The knife edges shall be square with the specimen surfaces and parallel to within 0.5°. For all types of knife edge, the notch opening displacement gauge shall be free to rotate about the points of contact between the gauge and knife edge.

NOTE For this reason, when inward pointing knife edges or razor blades are used, it may be necessary to use an enlarged notch mouth, as shown in Figure 6 and Figure 9 (see **7.3.1** and Figure 10).

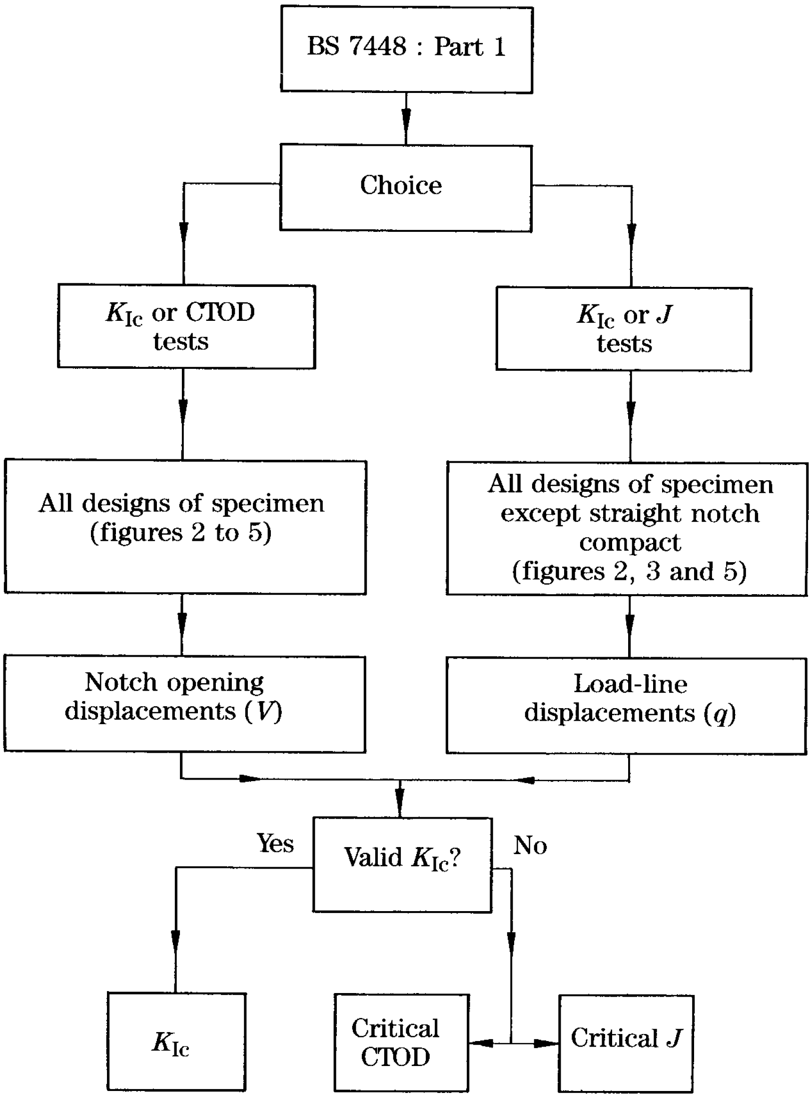
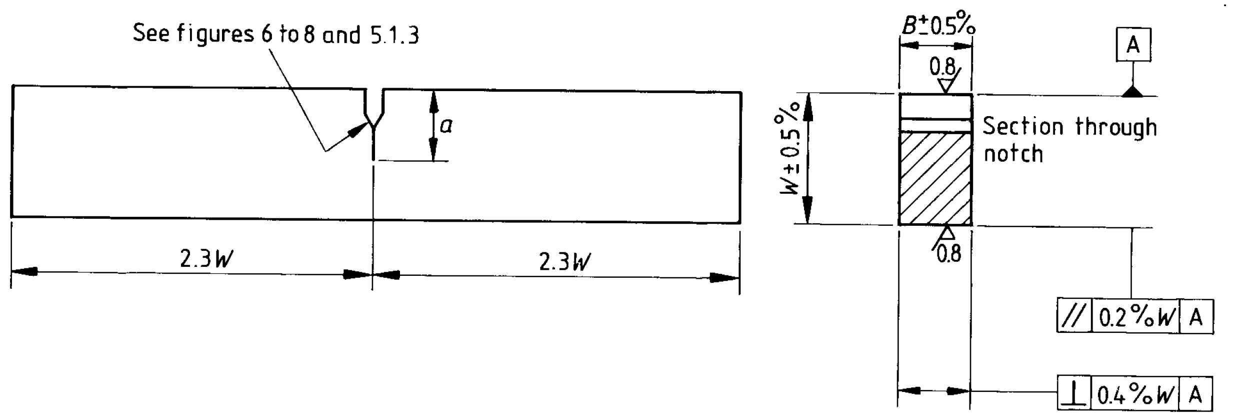
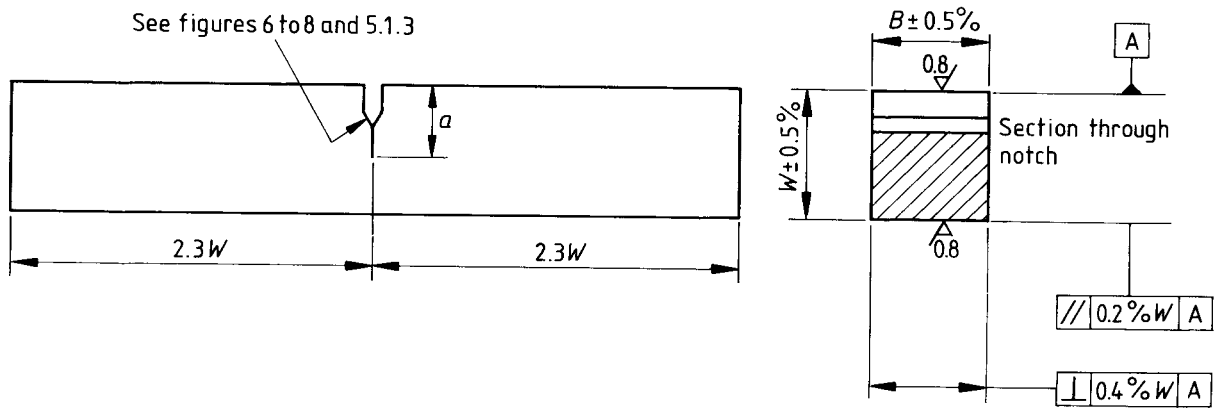


Figure 1 — Flow chart for choice of fracture toughness parameter, specimen design and displacement measurement



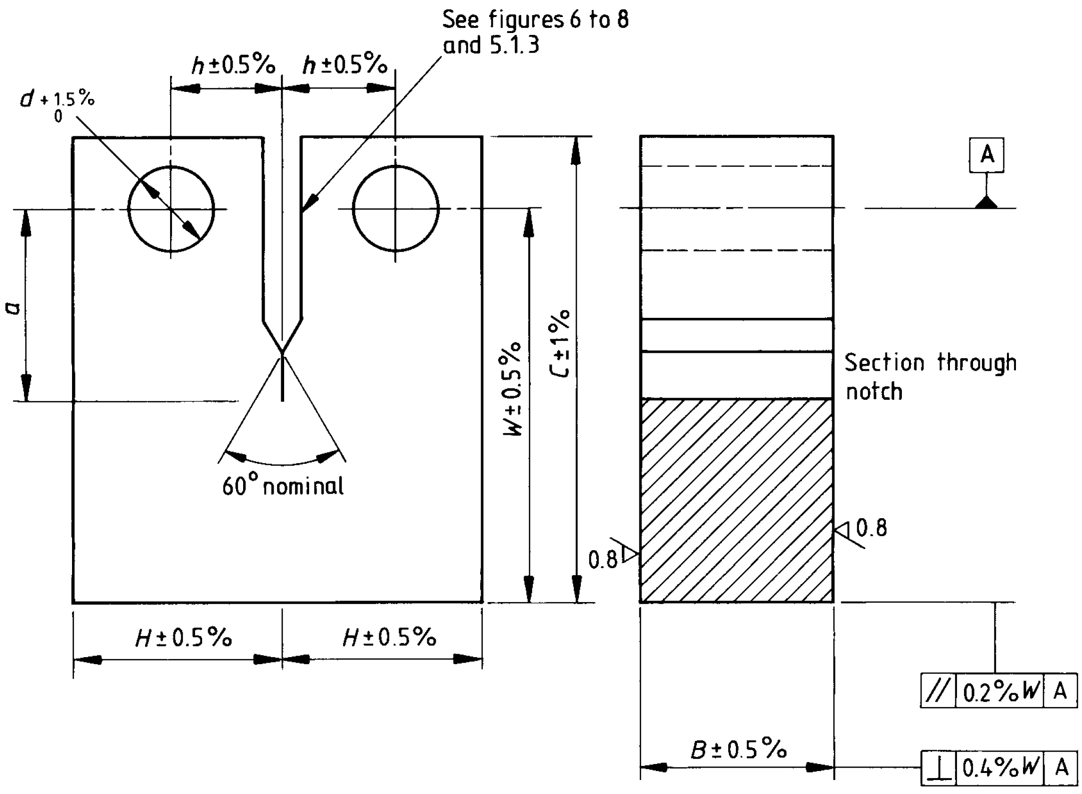
B is the thickness (see **5.1**)
Width, $W = 2B$
Crack length, $a = 0.45W$ to $0.55W$
Surface finish is in micrometres.

Figure 2 — Proportional dimensions and tolerances for a rectangular section bend specimen



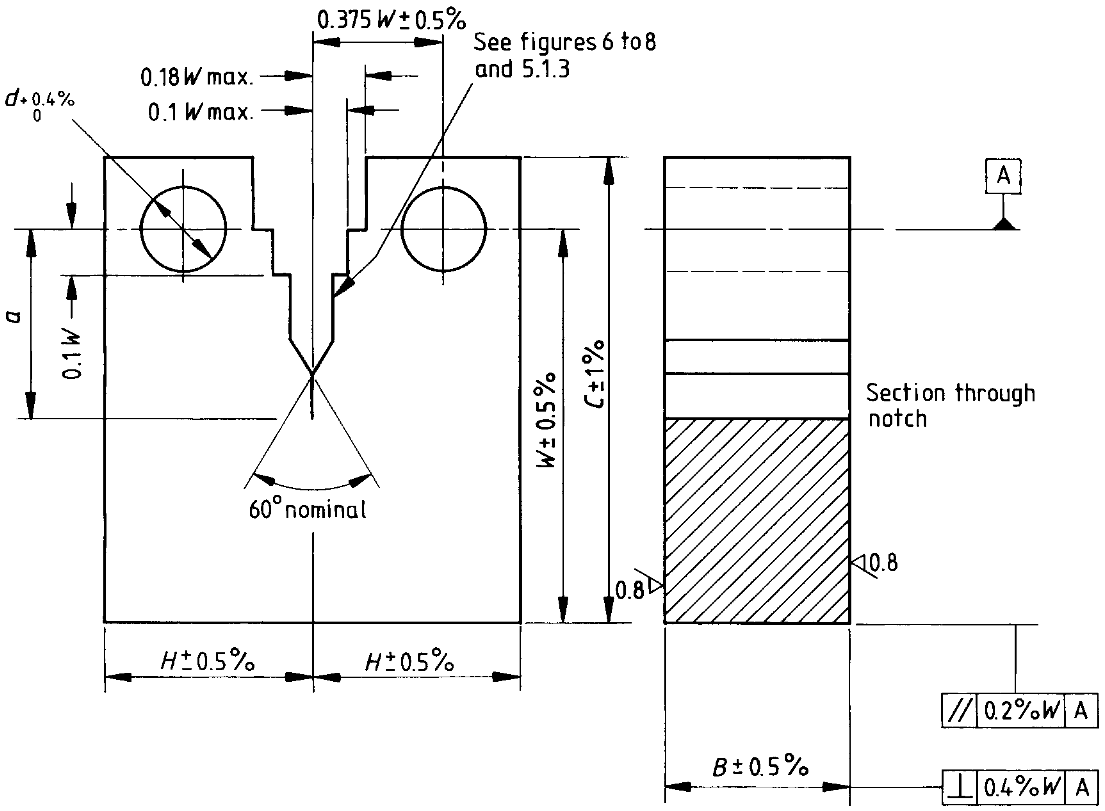
B is the thickness (see **5.1**)
Width, $W = B$
Crack length, $a = 0.45W$ to $0.55W$
Surface finish is in micrometres.

Figure 3 — Proportional dimensions and tolerances for a square section bend specimen



B is the thickness
W is the effective width
$W = 2B$ (see **5.1**)
Total width, $C = 1.25W$ min.
Half height, $H = 0.6W$
Hole diameter, $d = 0.25W$
Half distance between holes, $h = 0.275W$
Crack length, a $= 0.45W$ to $0.55W$
Surface finish is in micrometres.

Figure 4 — Proportional dimensions and tolerances for a straight notch compact specimen



B is the thickness
W is the effective width
$W = 2B$ (see **5.1**)
Total width, $C = 1.25W$ min.
Half height, $H = 0.6W$
Hole diameter, $d = 0.25W$
Crack length, $a = 0.45W$ to $0.55W$
Surface finish is in micrometres.

Figure 5 — Proportional dimensions and tolerances for a stepped notch compact specimen

5.2 Choice of specimen design

The choice of specimen design shall take into consideration the likely outcome of the test (see **5.3**), any preference for CTOD or *J* fracture toughness values (see **9.1**), and the crack plane orientation to be used in the test (see **6.2**).

NOTE 1 As indicated in Figure 1, all four designs of specimens (see Figure 2 to Figure 5) are suitable for the determination of K_{Ic} and CTOD values, and all except the straight notch compact specimen (see Figure 4) are suitable for the determination of *J* values.

NOTE 2 When notch opening displacement (V) is measured on the load-line, $V = q$ for a stepped notch compact specimen (see Figure 9), which is equally useful for the determination of K_{Ic}, CTOD and *J* values (see **9.1**).

NOTE 3 A compact specimen requires less material than a bend specimen, but requires more machining and more complicated fixtures for fatigue precracking and testing.

NOTE 4 For tests on a rectangular section (see **6.2** and Appendix B) it is normal (see **5.1.2**) to use a rectangular cross-section bend specimen (see Figure 2) or a compact specimen (see Figure 4 and Figure 5) for through thickness crack orientations (see X-Y and Y-X in Appendix B). It is also normal (see **5.1.2**) to use a square cross-section bend specimen (see Figure 3) for surface crack orientations (see X-Z and Y-Z in Appendix B).

5.3 Specimen dimensions necessary for a valid determination of K_{Ic}

NOTE 1 Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone are covered in BS EN ISO 12737.

The achievement of a valid K_{Ic} value will depend on the shape of the force versus displacement record (see **9.2**), the specimen size and form, and the 0.2 % proof strength (σ_{YS}) and toughness of the material at the temperature of interest. For a valid K_{Ic} measurement the specimen shall have a crack length (a), thickness (B) and the uncracked ligament ($W - a$) each not less than:

$$2.5\left(\frac{K_{\mathrm{Ic}}}{\sigma_{\mathrm{YS}}}\right)^2$$

NOTE 2 This requirement may be used to estimate the specimen size (full thickness or sub-size) for a valid K_{Ic} result. The estimate may be based on:

a) an estimate of the K_{Ic} of the material; or

b) the ratio of the 0.2 % proof strength (σ_{YS}) to Young's modulus (E), as given in Table 1.

Table 1 — Dimensions of specimens that may lead to valid K_{Ic} values

$\frac{\sigma_{\mathrm{YS}}}{E}$		**Crack length** (a) **Thickness** (B) **Ligament** ($W - a$)
Over	**Up to and including**	mm
—	0.005 0	100
0.005 0	0.005 7	75
0.005 7	0.006 2	63
0.006 2	0.006 5	50
0.006 5	0.007 1	38
0.007 1	0.008 0	25
0.008 0	0.009 5	13
0.009 5	—	6.5

6 Specimen preparation and fatigue precracking

6.1 Material condition

All specimens shall be tested in the finally heat treated, mechanically worked and environmentally conditioned state. Specimens shall be machined in this final state. However, for materials having a hardness greater than 600 HV 30 (see BS 427) for which machining is difficult, the final treatment may be carried out after machining provided that the required dimensions and tolerances on specimen size, shape and overall surface finish are met (see **6.3**) and that full account is taken of the effects of specimen size on metallurgical condition induced by certain heat treatments, e.g. water quenching of steels.

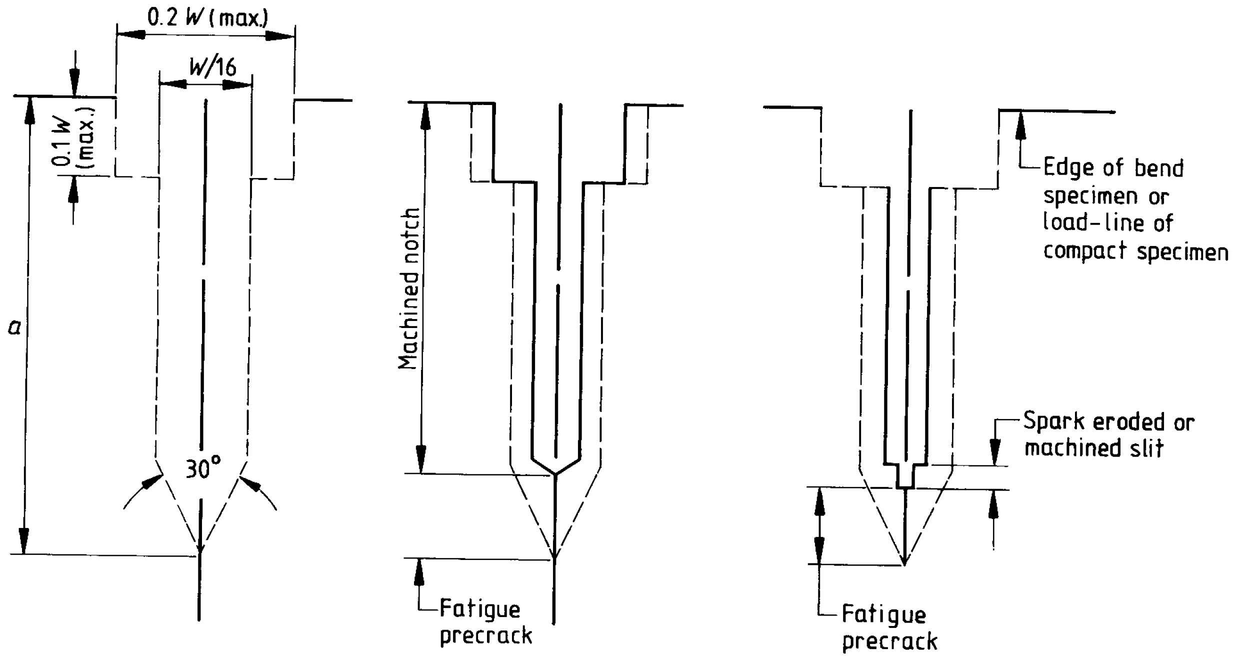
6.2 Crack plane orientation

The orientation of the crack plane shall be decided before machining (see **6.3**), identified in accordance with the co-ordinate systems in Appendix B, and recorded (see clause **11**).

NOTE The fracture toughness of a material is usually dependent on the orientation and direction of propagation of the crack in relation to the principal directions of mechanical working or grain flow.

6.3 Machining

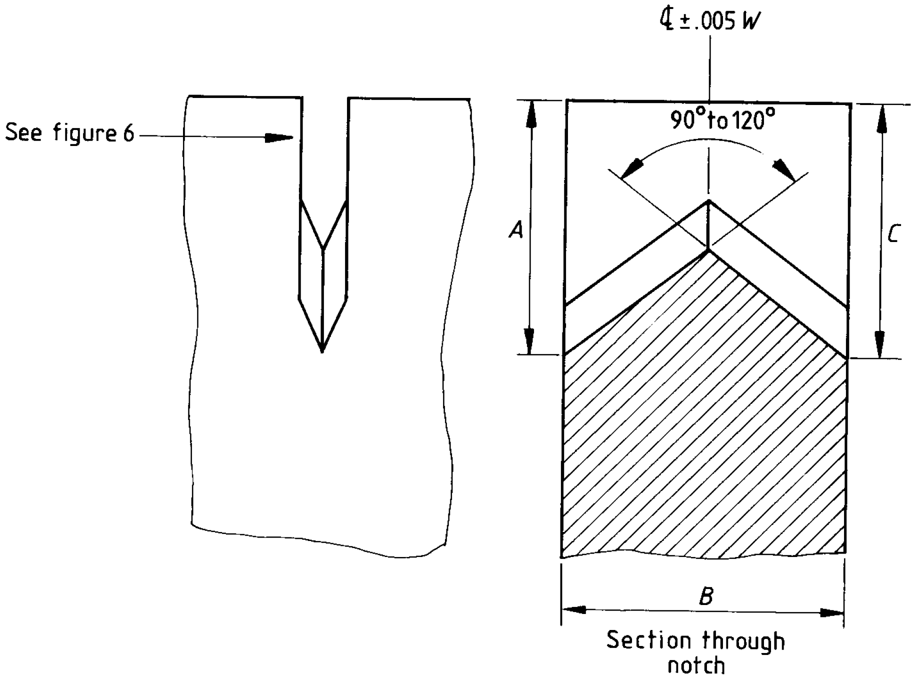
The sizes, shapes, dimensional tolerances and surface finishes for the specimens shall be as given in Figure 2 to Figure 5. Details of notches shall be as given in Figure 6, Figure 7 and Figure 8(a).



(a) Envelope

(b) Notch geometries

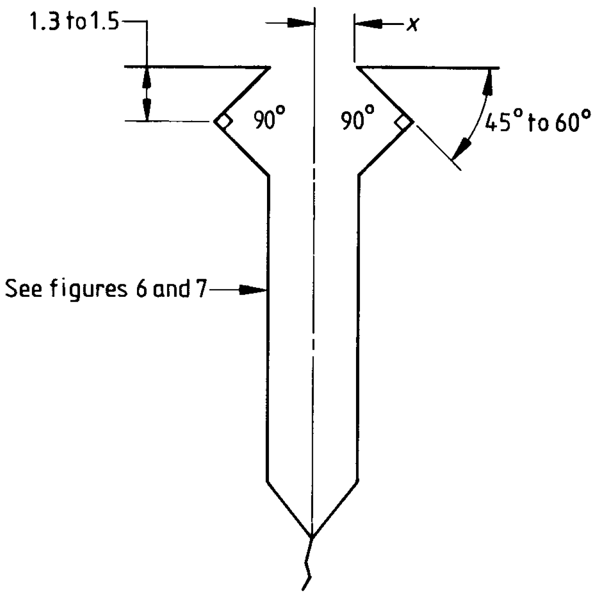
Figure 6 — Acceptable fatigue crack starter notches and fatigue crack configurations (see Figure 7 and Figure 8)



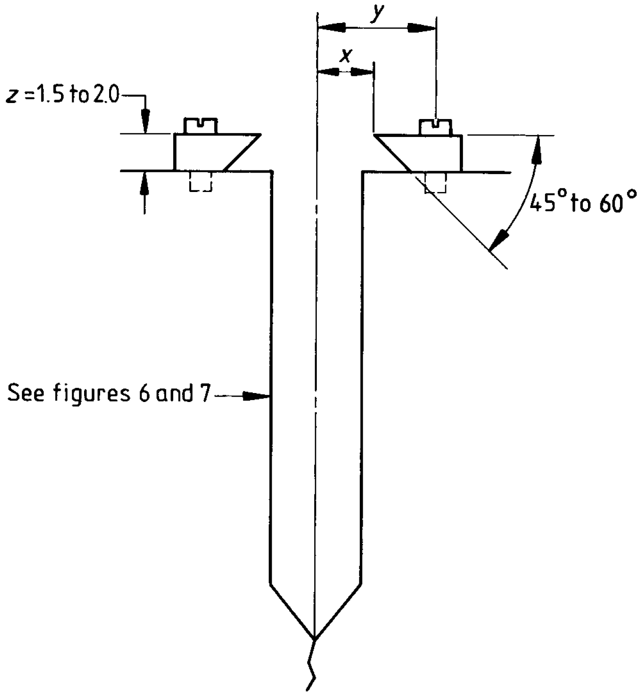
NOTE 1 $A = C$ within $0.010W$

NOTE 2 Cutter tip angle 90° max.

Figure 7 — Chevron notch



(a) Integral type



(b) Attached type

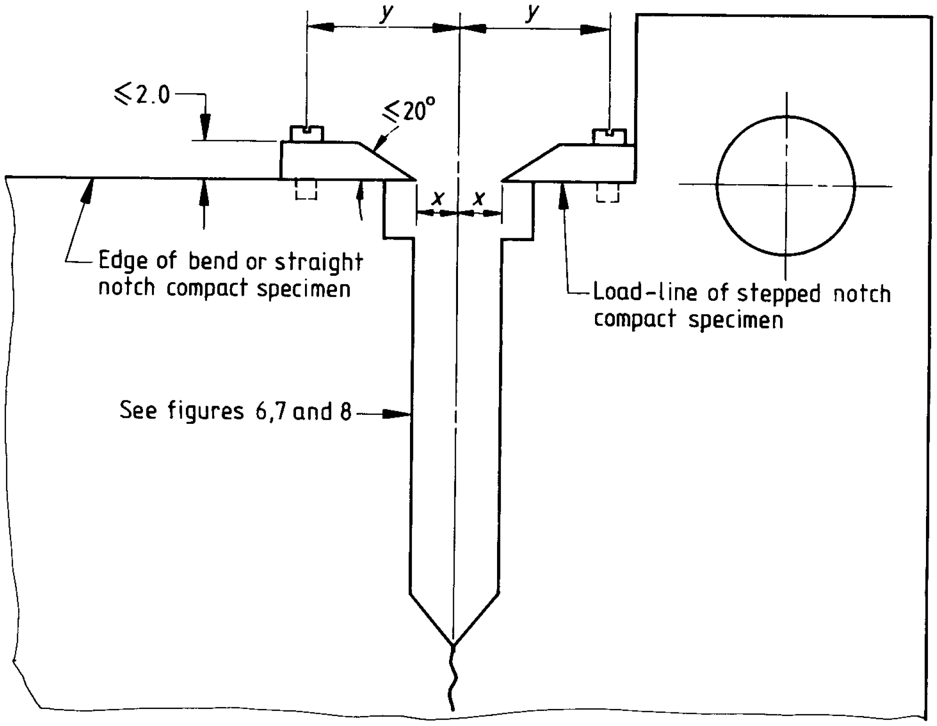
$2x \leq W/2$

$2y$ + screw thread diameter $\leq W/2$

All linear dimensions are in mm.

NOTE If the knife edges are glued or similarly attached to the edge of the specimen $2y$ = distance between points of attachment.

Figure 8 — Outward pointing knife edges and corresponding notch geometries (see Figure 9)



$2x \leq W/2$

$2y$ + screw thread diameter $\leq W/2$

All linear dimensions are in mm.

NOTE 1 If the knife edges are glued or similarly attached to the edges of the specimen $2y$ = distance between extreme points of attachment.

NOTE 2 If razor blades are used instead of inward pointing knife edges, the displacement will normally be measured at a point half the razor blade thickness above the load line (see **8.1.4**).

Figure 9 — Inward pointing knife edges and corresponding notch geometries (see Figure 8)

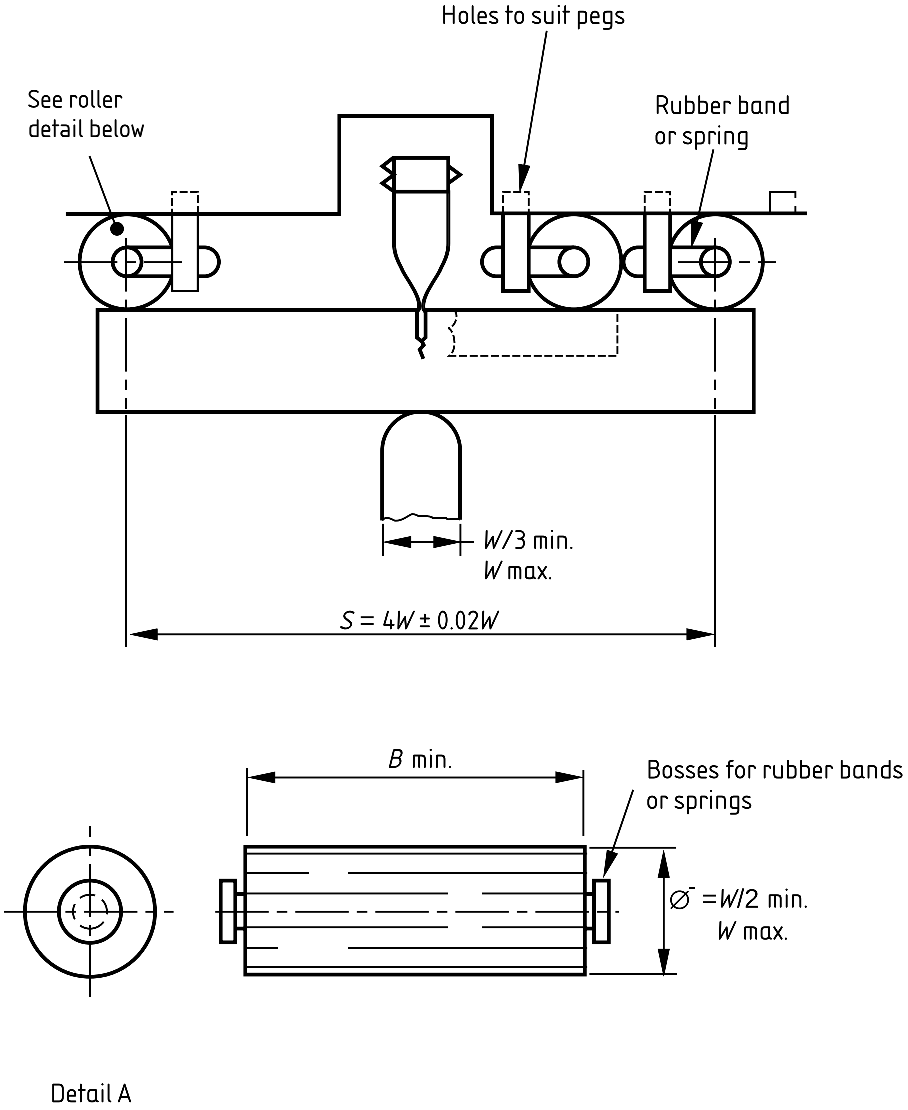


Figure 10 — Fixture for three point bend tests

6.4 Fatigue precracking

6.4.1 Fatigue precracking shall be done at room temperature with the material already in the finally heat-treated, mechanically worked and environmentally conditioned state unless particular fatigue precracking temperatures, and intermediate treatments between fatigue precracking and testing are required to simulate the conditions for a specific structural application.

6.4.2 Measure the specimen thickness (B) and width (W) as described in **8.1.2** and **8.1.3**, respectively. The measured values of specimen thickness (B) and width (W) shall be recorded and used to determine the maximum fatigue precracking force (F_f) according to **6.4.5** or **6.4.6**.

6.4.3 The test fixtures for fatigue precracking (see **7.5**), shall be such that the stress distribution is uniform through the specimen thickness (B) and symmetrical about the plane of the prospective crack.

6.4.4 The fatigue precracking force shall be measured to an accuracy within ±2.5 %.

6.4.5 For the three point bend specimens illustrated in Figure 2 and Figure 3, the maximum fatigue precracking force [F_f, see **6.4.7**a)], during the final 1.3 mm or 50 % of precrack extension, whichever is less [see **6.4.7**c)] shall be the lower of:

a)

$$F_f = \frac{B(W-a)^2(\sigma_{YSP} + \sigma_{TSP})}{4S}$$

b)

a force corresponding to

$$\frac{\Delta K}{E} = 3.2 \times 10^{-4} \mathrm{m}^{0.5}$$

c)

$$F_f = \frac{K_f B W^{1.5}}{S \times f\left(\frac{a}{W}\right)}$$

(in tests that give valid K_{Ic} values [see **5.3** and **9.2**)]

where

$K_f = 0.6\left(\frac{\sigma_{YSP}}{\sigma_{YS}}\right)K_Q$;

K_Q is determined according to **9.2.3.2**;

a is an assumed crack length $\leq a_o$; and

$f\left(\frac{a_o}{W}\right)$ is given by equation (3) in **9.2.3.2** and in tabular form in Table 2.

Table 2 — Values of $f\left(\frac{a_o}{W}\right)$ for three point bend specimens[a]

$\frac{a_o}{W}$	$f\left(\frac{a_o}{W}\right)$
0.450	2.29
0.455	2.32
0.460	2.35
0.465	2.39
0.470	2.43
0.475	2.46
0.480	2.50
0.485	2.54
0.490	2.58
0.495	2.62
0.500	2.66
0.505	2.70
0.510	2.75
0.515	2.79
0.520	2.84
0.525	2.89
0.530	2.94
0.535	2.99
0.540	3.04
0.545	3.09
0.550	3.14

[a] For the purposes of fatigue precracking an assumed value of crack length, a, may be substituted for a_o.

6.4.6 For the compact specimens illustrated in Figure 4 and Figure 5, the maximum precracking force (F_f) [see **6.4.7**a)] during the final 1.3 mm or 50 % of precrack extension, whichever is less [see **6.4.7**c)] shall be the lower of:

a)

$$F_f = \frac{0.2B\,(W-a)^2(\sigma_{YSP}+\sigma_{TSP})}{(2W+a)}$$

b)

a force such that $\frac{\Delta K}{E} = 3.2 \times 10^{-4}\ \text{m}^{0.5}$

c)

$$F_f = \frac{K_f\,BW^{0.5}}{f'\left(\frac{a}{W}\right)}$$ (in tests that give valid K_{Ic} values [see **5.3** and **9.2**c)]

where

$K_f = 0.6\left(\frac{\sigma_{YSP}}{\sigma_{YS}}\right)K_Q$;

K_Q is determined according to **9.2.3.3**;

a is an assumed crack length $\leq a_o$; and

$f'\left(\frac{a_o}{W}\right)$ is given by equation (5) in **9.2.3.3** and in tabular form in Table 3.

6.4.7 A fatigue crack of restricted shape and size shall be developed from the tip of the machined notch in the specimen as specified in a) to e).

a) For the initial fatigue precrack extension, the maximum stress intensity factor shall not exceed $1.3K_f$. The fatigue force ratio (R) shall be in the range 0 to 0.1.

NOTE To expedite crack initiation (see **5.1.3**), one or more cycles of opposite sign and equal or lower magnitude force may be applied first.

b) For all four designs of specimen (see Figure 2 to Figure 5), the ratio a/W shall be in the range 0.45 to 0.55 (see **8.7**).

c) The minimum fatigue crack extension shall be the larger of 1.3 mm or 2.5 % of the specimen width (W). (See **8.7**.)

d) The difference between the two crack length measurements on the surfaces of the specimen, measured to ±0.05 mm, shall not exceed 15 % of the average of the two measurements.

e) The crack tip shall be within a limiting envelope as shown in Figure 6. The plane of the fatigue precrack shall always be within 10° of the plane of crack extension. (See **5.1.3** and **8.7**.)

Table 3 — Values of $f'\left(\frac{a_0}{W}\right)$ for compact specimens[a]

$\frac{a_0}{W}$	$f'\left(\frac{a_0}{W}\right)$
0.450	8.34
0.455	8.46
0.460	8.58
0.465	8.70
0.470	8.83
0.475	8.96
0.480	9.09
0.485	9.23
0.490	9.37
0.495	9.51
0.500	9.66
0.505	9.81
0.510	9.96
0.515	10.12
0.520	10.29
0.525	10.45
0.530	10.63
0.535	10.80
0.540	10.98
0.545	11.17
0.550	11.36

[a] For the purposes of fatigue precracking an assumed value of crack length, a, may be substituted for a_0.

7 Test equipment

7.1 Calibration

The calibration of measuring apparatus shall be traceable to the National Physical Laboratory either directly or indirectly through a hierarchical chain such as that provided by the National Measurement Accreditation Service (NAMAS) accredited Calibration Laboratories in accordance with the accuracy demanded by the test.

This includes automatic equipment used for the determination of any one of the parameters described in this standard.

7.2 Force application

7.2.1 The machine for force application shall be capable of applying force at rates high enough to achieve the rates of change of stress intensity factor (K) specified in **8.5**.

7.2.2 The systems for force application and recording shall allow the force signal to be recorded against the displacement of the test specimen. The combination of force sensing and recording device shall comply with grade 1.0 of BS 1610-1.

NOTE These requirements will permit the value of the force (F) as used in clause **9** to be determined from the test record to an accuracy within ±1 %.

7.3 Displacement measuring devices[5]

7.3.1 The design of the notch opening displacement gauge, knife edges and specimen (see **5.1.3**) shall allow free rotation of the points of contact between the gauge and knife edges. The gauge shall have an electrical output that represents the displacement (V or q) that occurs during the test. The response of the gauge shall be such that the deviation from true displacement shall be not more than ±0.003 mm for displacements up to 0.3 mm and not more than ±1 % of the recorded value for larger displacements. The gauge shall be calibrated before each determination, except where identical specimens and conditions are used, when less frequent calibration may be agreed between the parties concerned.

NOTE The procedure outlined in BS 3846 for calibration either in a rig or using an elastic device, should be used for checking the response of the gauge, but other methods capable of the same accuracy are not excluded. Calibration is of particular importance for low temperature tests, where a gauge is most likely to give spurious readings. When the gauge is well insulated from the specimen, an ambient temperature calibration will usually be adequate; however, it should be demonstrated that the calibration is satisfactory for the test condition.

7.3.2 The gauge used to measure displacements of the three point bend specimen along the central line of the applied force (F) shall have an accuracy equal to that of the notch opening displacement gauge (see **7.3.1**).

7.4 Monitoring and recording equipment

The response time of monitoring and recording equipment shall be less than 20 % of the rise time interval of the input signal.

NOTE Methods that may be used to check this are given in BS 7448-3[6].

7.5 Testing fixtures

7.5.1 Three point bend specimens (see Figure 2 and Figure 3) shall be tested using a loading fixture designed to reduce friction at the loading points to a minimum. Achieve this by allowing the rollers to rotate and move apart slightly, thus maintaining rolling contact throughout the test. The diameter of the rollers shall be between W and $W/2$.

NOTE A design that has proved satisfactory is shown in Figure 10.

7.5.2 Compact specimens shall be loaded in tension using a clevis and pin arrangement that has been designed to minimize friction. This arrangement shall permit alignment as the specimen is loaded.

NOTE Designs of clevis that have proved satisfactory are shown in Figure 11 and Figure 12.

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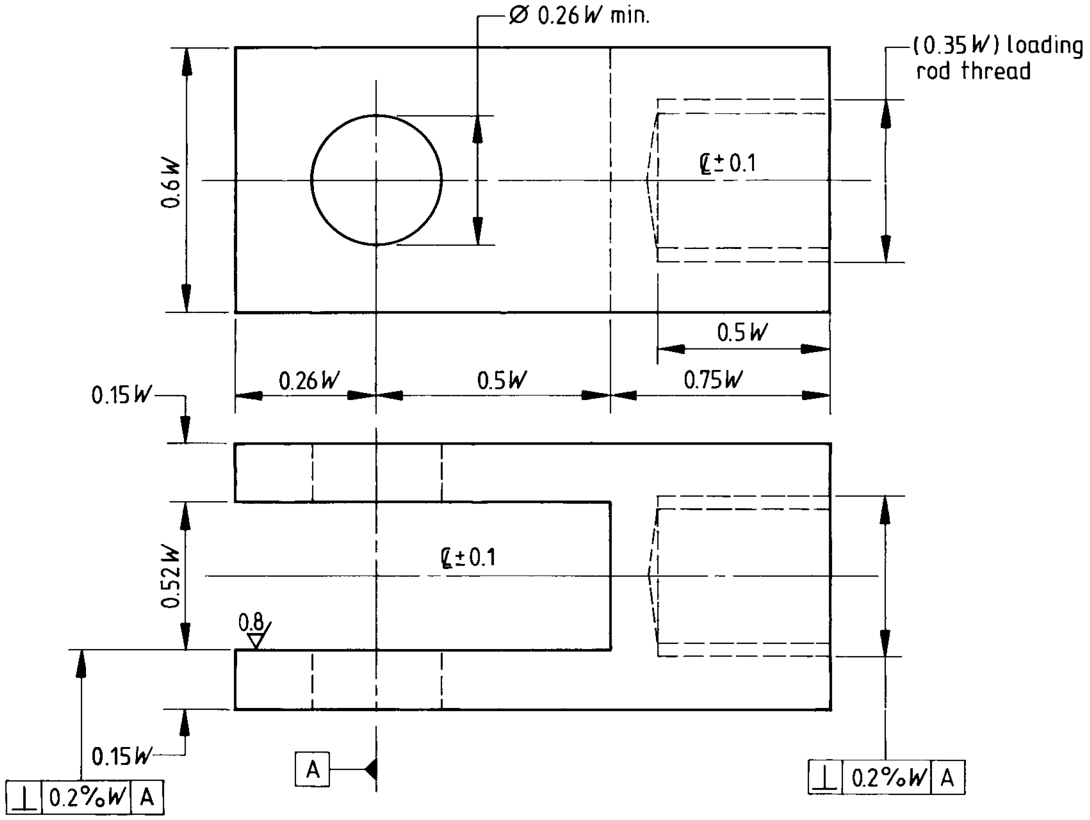
[5] For information on the availability of notch opening displacement gauges write to the Information Centre, BSI Chiswick High Road, London W4 4AL.

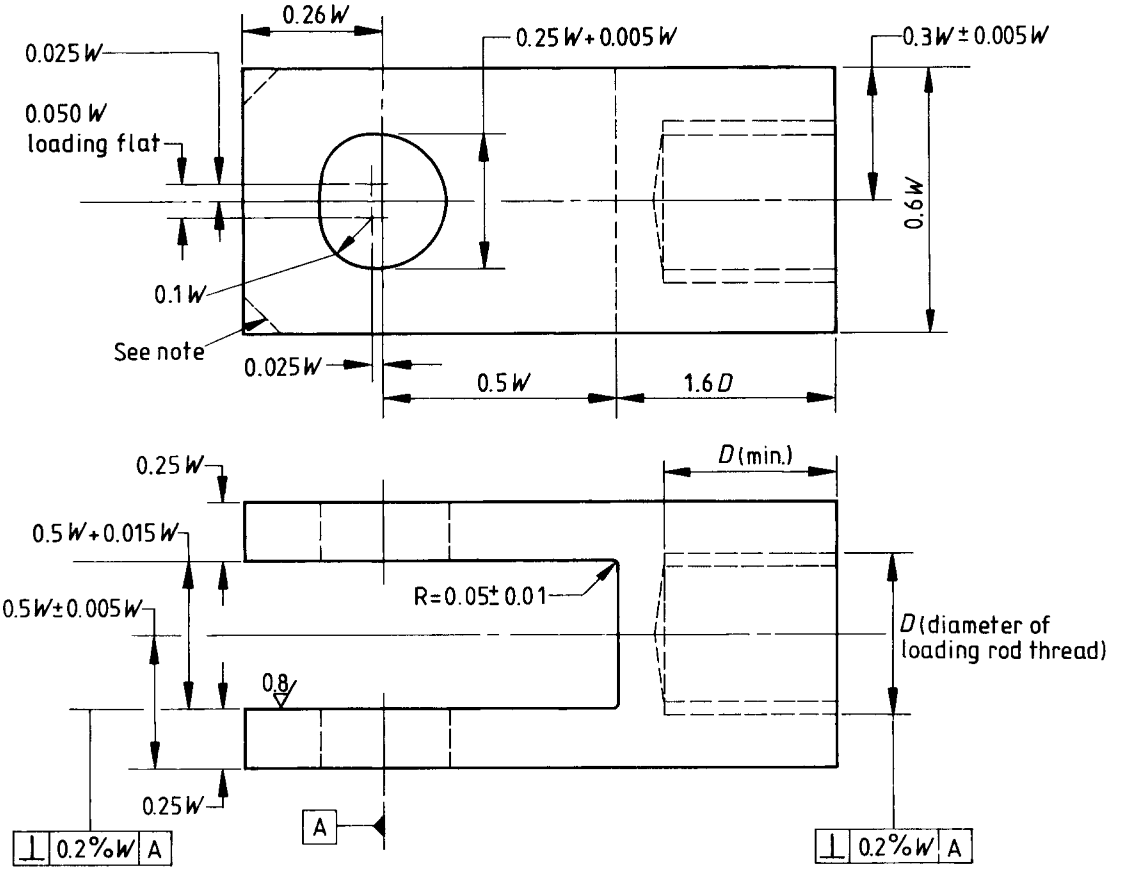
[6] In preparation.



All dimensions are in mm.

Surface finish is in micrometres.

Figure 11 — Typical design of clevis for applying a tensile force to a compact specimen using a circular hole in the clevis, and a pin having a diameter of $0.24W - 0.005W, -0.015W$ (see Figure 12)



All dimensions are in mm.

Surface finish is in micrometres.

NOTE Corners of the clevis may be removed if necessary to accommodate the clip gauge.

Figure 12 — Typical design of clevis for applying a tensile force to a compact specimen using a hole with a flat in the clevis, and a pin having a diameter of $0.24W + 0.000W$, $-0.005W$ (see Figure 11)

8 Test procedure

8.1 Specimen measurement

NOTE Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone are covered in BS EN ISO 12737.

8.1.1 The dimensions of the specimen shall comply with clause **5**. Measurements shall be made both before testing, in accordance with **8.1.2** to **8.1.5**, and after testing, in accordance with **8.7**. The measurements shall be recorded and used for the calculation of K_{Ic} or CTOD and/or J values according to clause **9**.

8.1.2 Measure the specimen thickness to ±0.025 mm or ±0.1 %, whichever is larger, at not less than three equally spaced positions along the anticipated crack extension path. The average of these measurements shall be taken as the thickness (B).

8.1.3 Measure the specimen width to the nearest ±0.025 mm or ±0.1 %, whichever is larger, at not less than three equally spaced positions across the specimen thickness on a line not further than 10 % of the nominal width away from the crack plane. The average of these measurements shall be taken as the width (W).

8.1.4 When outward pointing attached knife edges [Figure 8(b)] are used, the knife edge thickness (z) shall be measured. If razor blades are used for the knife edges, the half thickness of these shall be taken as the dimension z.

NOTE 1 If z is less than $0.002a$, it may be ignored.

NOTE 2 When integral or inward pointing attached knife edges are used [see Figure 8(a) and Figure 9], the dimension z is equal to zero.

8.1.5 When a straight notch compact specimen is used, measure the dimension ($C - W$).

8.2 Three point bend testing

Set up the test fixture (see Figure 10) so the line of action of the applied force passes midway between the centres of the rollers within ±1 % of the distance between these centres. Adjust the span (S) to $4W \pm 0.02W$, and record the actual span to ±0.5 %. Locate the bend specimen with the crack tip midway between the rollers to ±1 % S, and square to the roller axes to within ±2°.

Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone shall be performed in accordance with BS EN ISO 12737.

For tests to measure K_{Ic} or CTOD values, seat the notch opening gauge on the knife edges after squeezing the gauge beams together to maintain spring contact between the knife edges and beam seats.

NOTE 1 The notch opens during the test.

For tests to measure J values, arrange either direct or indirect measurements of load-line displacement (q) as described in Appendix C.

NOTE 2 When an indirect load-line displacement measurement is made relative to the loading fixture or testing machine, errors from two sources are possible. These are the elastic compression in the fixtures and testing machine, and elastic and plastic indentation of the specimen at the three loading points.

8.3 Compact tension testing

Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone shall be performed in accordance with BS EN ISO 12737.

For tests to measure K_{Ic} or CTOD values using a straight notch compact specimen (see **5.2** and Figure 4), seat the notch opening gauge on the knife edges on the edge of the specimen (see Figure 8 and Figure 9), as described in **8.2**.

For tests to measure K_{Ic}, CTOD or J values using a stepped notch compact specimen (see **5.2** and Figure 5), seat the notch opening gauge on the attached knife edges on the load-line of the specimen (see Figure 9), as described in **8.2**.

8.4 Specimen test temperature

The temperature shall be controlled and recorded to an accuracy of ±2 °C. Place a thermocouple or platinum resistance thermometer in contact with the surface of the specimen in a region not further than 2 mm from the crack tip, or on the surface within the machined notch near the centre of the specimen. Tests shall be made in situ in suitable low or high temperature media. Before testing in a liquid medium, the specimen shall be retained in the liquid for at least 30 s/mm of thickness (B) after the specimen surface has reached the test temperature. When using a gaseous medium, a soaking time of at least 1 min/mm of thickness shall be used.

If the specimen is transferred from one medium to another, and both are at the test temperature after the required soaking time has elapsed, then the specimen shall be soaked in the new medium for the time taken for the transfer, after the test temperature is again reached.

NOTE The temperature change during the transfer should not exceed 2 °C.

8.5 Testing

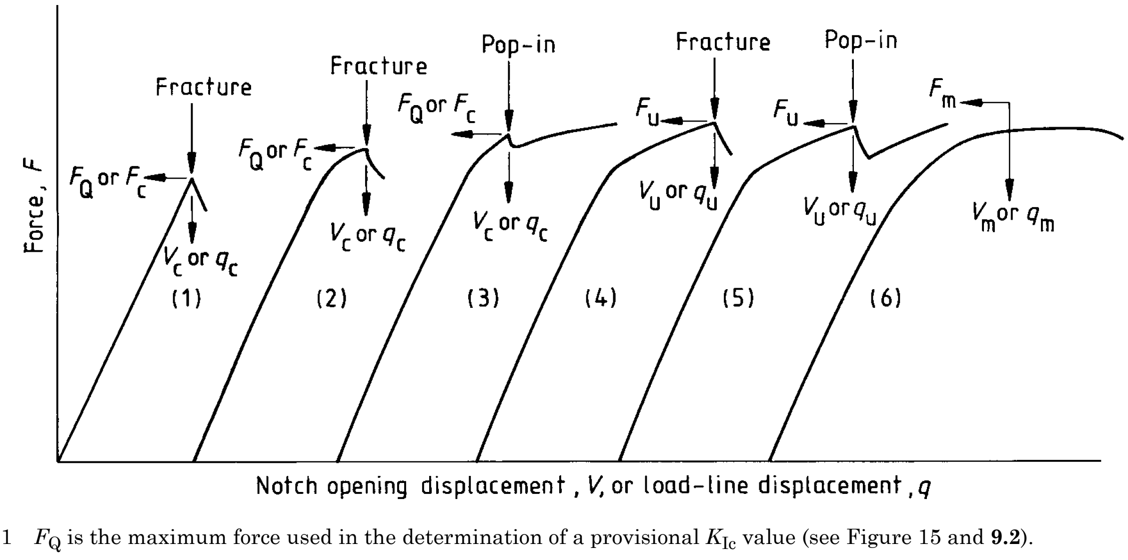
Using displacement control apply a machine displacement such that a constant K is achieved within the range 0.5 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ to 3.0 $\text{MPa}\cdot\text{m}^{0.5}\text{s}^{-1}$ during linear elastic specimen deformation (see **7.2.1**). Record the value of K achieved (see clause **11**).

8.6 Recording

Make a record of the output of the force sensing device (see **7.2.2**) versus the output from the notch opening displacement gauge (see **7.3.1**) and/or the load-line displacement of a three point bend specimen (see **7.3.2** and Appendix C). When an autographic record is made for a subsequent manual analysis (see **9.1**), the initial slope of the force versus notch opening displacement, or force versus load-line displacement record shall be between 0.85 and 1.5.

NOTE Non-linearity often occurs at the beginning of a record. Since this may make it difficult to analyse the record (see **9.2.2**), it may be possible to minimize this non-linearity by a preliminary loading and unloading with a force not exceeding F_f (see **6.4.5** and **6.4.6**). However, non-linearity caused by crack closure cannot be minimized.

Continue the test until the specimen can sustain no further increase in applied force (see Figure 13).



NOTE 1 F_Q is the maximum force used in the determination of a provisional K_{Ic} value (see Figure 15 and **9.2**).

NOTE 2 F_c, F_u and F_m correspond to either δ_c, δ_u and δ_m respectively, or J_c, J_u, and J_m, respectively.

NOTE 3 Pop-in behaviour is a function of the testing machine/specimen compliance and the recorder response rate.

Figure 13 — Characteristic type of force versus displacement records in fracture test

8.7 Crack measurements after testing to fracture

8.7.1 *General*

After the test has been completed, the fracture surface of the specimen shall be examined and measured to determine the original crack length (a_0) and the amounts of any stable crack extension (Δa), according to **8.7.2** and **8.7.3** respectively.

NOTE When the test is terminated before the specimen has fractured in half it will be necessary to break the specimen open to expose the fatigue precrack and any crack extension that has occurred during the test. The latter may be marked by heat-tinting, or applying a few fatigue cycles before breaking the specimen open. This should be done with care to minimize any additional deformation of the specimen. Cooling ferritic steels enough to ensure brittle behaviour on breaking open the specimen will be helpful.

8.7.2 *Original crack length*

Measure the crack length (a) to the tip of the fatigue precrack to ±0.25 % a or ±0.05 mm, whichever is the greater. The measurements shall be made at nine equally spaced points where the outer points are located at 1 % B from the specimen surface. The original crack length (a_0) shall be obtained by firstly averaging the two measurements at the outer points and then averaging this value with the seven inner points. This will involve the weighted summation of the crack length dimensions being divided by eight.

For the test to be valid the crack length (a_0) shall meet the following requirements.

a) The ratio a_0/W shall be within the range 0.45 to 0.55.

b) The difference between any two of the nine crack length measurements shall not exceed 10 % a_0.

c) No part of the fatigue precrack front shall be closer to the crack starter notch than 1.3 mm or 2.5 % W, whichever is the larger.

d) The fatigue precrack shall be within the appropriate envelope for the corresponding a_0/W value (see Figure 6).

e) The plane of the fatigue precrack shall be within 10° of the plane of crack extension.

The average crack length (a_0) shall be recorded for the determination of K_{Ic}, CTOD, or J values, according to clause **9**.

NOTE Where there is no evidence of stable crack extension (see **8.7.3**) five equally spaced measurements of fatigue crack length may be substituted for the nine equally spaced measurements referred to above, with the agreement of the parties concerned.

8.7.3 *Stable crack extension*

8.7.3.1 If the specimen fails by brittle crack extension (see **2.10**) prior to the first attainment of a maximum force plateau [see Figure 13, record type (4)], the fracture surface shall be examined for evidence of stable crack extension (see **2.11**), in the region between the fatigue precrack front and the start of brittle crack extension.

NOTE Evidence of stable crack extension will generally appear as a fibrous thumbnail ahead of the fatigue precrack tip.

8.7.3.2 When there is evidence of stable crack extension, this shall be measured to ±0.05 mm. The measurements shall be made at nine equally spaced points where the outer points are located at 1 % B from the specimen surfaces. The stable crack extension (Δa) shall be obtained by firstly averaging the two measurements at the outer points and then averaging this value with the seven inner points. This will involve the weighted summation of the crack extension dimensions being divided by eight.

8.7.3.3 When there is evidence of arrested brittle crack extension and subsequent stable crack extension, and this can be associated with pop-in behaviour of subsequent fracture prior to the first attainment of a maximum force plateau (see Figure 13), the total amounts of Δa prior to each pop-in and fracture shall be measured and recorded as specified in **8.7.3.2**.

NOTE The total amounts of Δa will include any stable crack extension ahead of the fatigue precrack, and any stable crack extension associated with any pop-in before the particular pop-in or fracture behaviour being recorded.

8.7.3.4 The shape of the fatigue precrack, and any evidence of stable crack extension or arrested brittle crack extension prior to the first attainment of a maximum force plateau, shall be recorded on a diagram of the fracture surface. The diagram shall also record any unusual features of the fracture surface, such as splits or delaminations in planes that are perpendicular to the fracture surface.

NOTE Splits and delaminations can result in pop-ins with no arrested brittle crack extension in the plane of the fatigue precrack.

9 Analysis of test data

9.1 General

Plane strain fracture toughness, K_{Ic}, CTOD, or J values are determined from a knowledge of the dimensions of the test specimen (B, W and $C - W$ determined in accordance with **8.1**, a_{o} determined in accordance with **8.7**, and where appropriate, z determined in accordance with **8.1.4**), the 0.2 % proof strength (σ_{YS}) at the temperature of the fracture test, and specific data from the force versus displacement record of the fracture test (see **9.2**, **9.3** and **9.4**).

When the fracture occurs under elastic-plastic conditions, and it is not possible to determine valid K_{Ic} values (see **9.2.4**), it will normally be possible to determine either critical CTOD or critical J values, as described in **9.3** and **9.4**, respectively.

Data for the determination of K_{Ic} are obtained from either a force (F) versus notch opening displacement (V) record, or a force (F) versus load-line displacement (q) record. However, data for the determination of CTOD values shall be obtained from a force (F) versus notch opening displacement (V) record, and data for the determination of J values shall be obtained from a force (F) versus load-line displacement (q) record.

NOTE 1 For a stepped notch compact specimen (see Figure 5), the notch opening displacement (V) is equal to the load-line displacement (q). Therefore, the same force versus displacement record may be used to determine values of both CTOD and J.

The force versus displacement record of the test will usually have the appearance of one of the six types shown in Figure 13. Records of types (1), (2) and (3), involving crack extension within or close to the linear force versus displacement behaviours, are most likely to result in valid plane strain fracture toughness, K_{Ic}, values (see **9.2**). The highest values of elastic-plastic fracture toughness (CTOD or J) will be associated with record types (4), (5) and (6).

NOTE 2 A record of the first attainment of a maximum force plateau may show a more abrupt drop in force than is shown by the type (6) record in Figure 13, especially in tests on high strength materials.

Pop-ins (see Figure 14) giving both force drops (y) and displacement increases (x) of less than 1 % shall be ignored. All other pop-ins shall be considered significant, and shall be assessed according to either:

a) the procedure given in **9.2** for valid K_{Ic} determinations; or

b) the following equation for force drop at constant displacement [2], and the procedures in **9.3** and **9.4** for critical CTOD and critical J determinations, respectively.

$$d_{\mathrm{n}}\ \%\ F_1 = 100\left[1 - \frac{D_1}{F_1}\left(\frac{F_{\mathrm{n}} - y_{\mathrm{n}}}{D_{\mathrm{n}} + x_{\mathrm{n}}}\right)\right]\ \% \qquad (1)$$

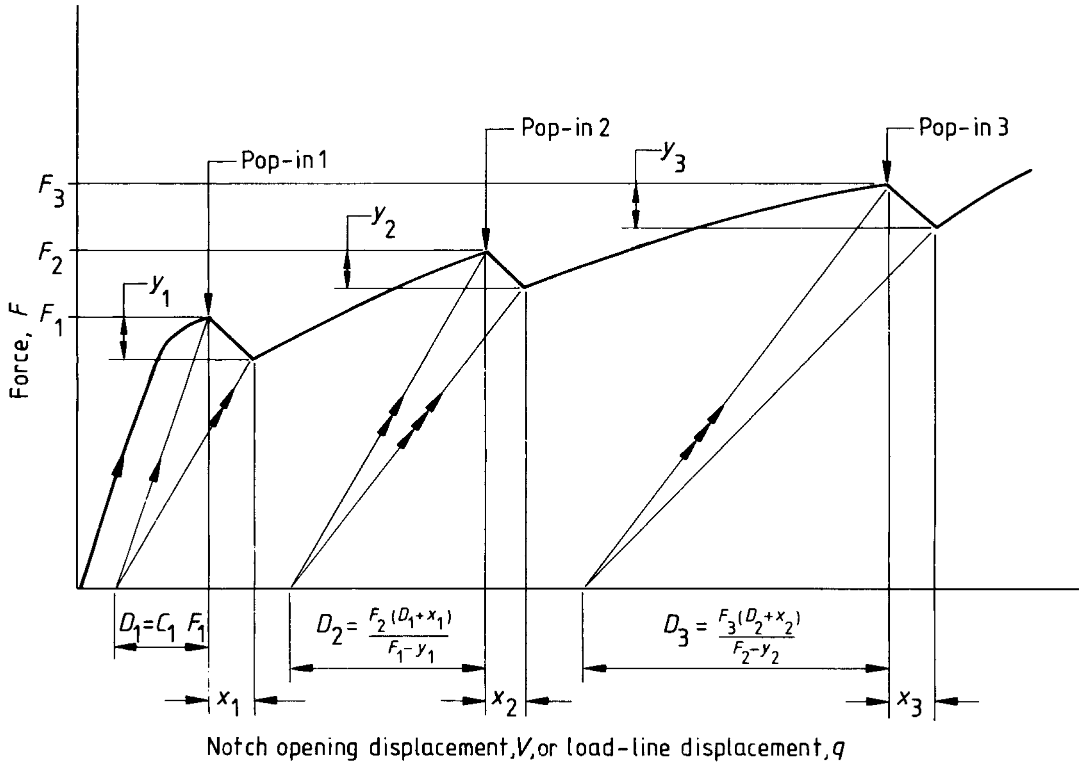
where the main symbols are as defined in Figure 14, and the subscript n indicates the particular pop-in being assessed.

9.2 Determination of plane strain fracture toughness, K_{Ic}

9.2.1 *General*

Determination of K_{Ic} for materials and conditions for which it is appropriate to determine fracture toughness in terms of K_{Ic} alone shall be performed in accordance with BS EN ISO 12737.

Interpret the test record according to **9.2.2**, calculate a provisional result, K_{Q}, according to **9.2.3**, and then determine whether the specimen used to determine this K_{Q} value meets the size requirements appropriate to the 0.2 % proof strength (σ_{YS}) of the specimen at the time of the test according to **9.2.4**.



NOTE 1 C_1 is the initial compliance.

NOTE 2 D represents V or q.

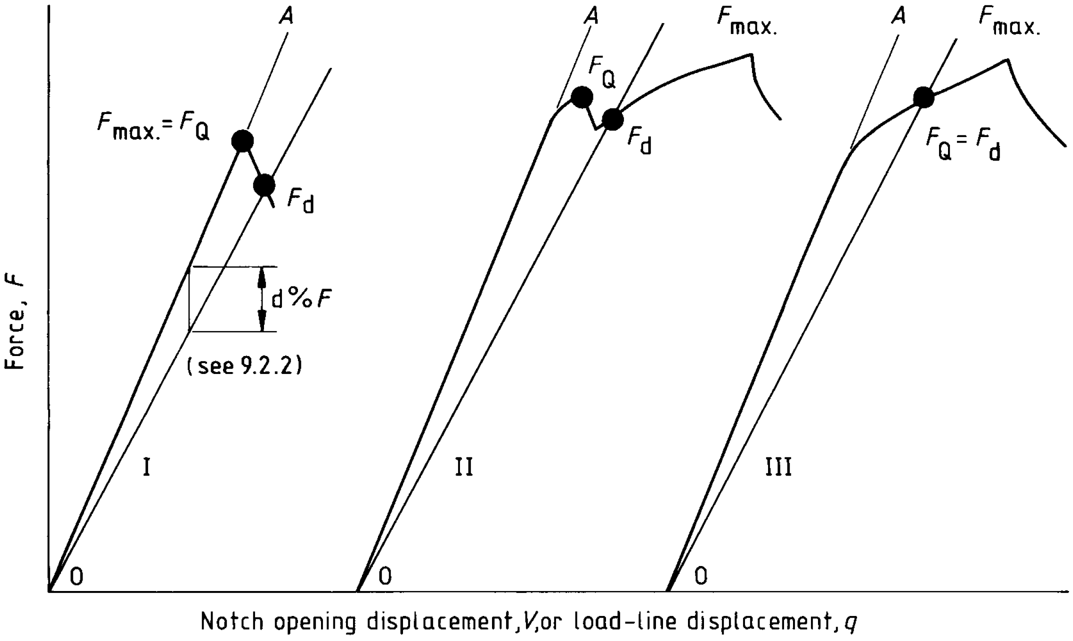
Figure 14 — Assessment of pop-in behaviour (see **9.2**, **9.3** and **9.4**)

9.2.2 *Interpretation of test record*

Referring to Figure 15, draw the line OF_d through the origin with a slope of d % F less than the slope of the tangent OA to the initial part of the record. The value of d % F shall be 5 % when interpreting a force (F) versus notch opening displacement (V) record, and, for a bend specimen only, 4 % when interpreting a force (F) versus load-line displacement (q) record. Also, for the purpose of constructing the line OF_d, the test record for the stepped notch compact specimen (see Figure 5) shall be treated as an F versus V record, i.e. ignoring the fact that for this specimen, V is also equal to q.

F_Q is either the highest force that precedes F_d, as shown in Figure 15 for the type I to II records, or the force that coincides with F_d, as shown in Figure 15 for the type III record.

Record the maximum force (see Figure 15) sustained by the specimen, and calculate the ratio F_{max}/F_Q. If this ratio exceeds 1.10, it is possible that K_Q bears insufficient relation to K_{Ic}, and the record shall be interpreted according to **9.3** or **9.4**. If F_{max}/F_Q is less than 1.10, proceed to calculate K_Q according to **9.2.3**.



NOTE The d % F offset slopes are exaggerated for clarity.

Figure 15 — Definition of F_Q (for the determination of K_Q)

9.2.3 *Calculation of* K_Q

9.2.3.1 Calculate K_Q from F_Q using the relationships in **9.2.3.2** and **9.2.3.3**, and the values of B and W determined according to **8.1**, and a_o determined according to **8.7**.

9.2.3.2 For bend specimens calculate K_Q using equation (2) [3].

$$K_Q = \frac{F_Q S}{B W^{1.5}} \times f\left(\frac{a_o}{W}\right) \tag{2}$$

where

$$f\left(\frac{a_o}{W}\right) = \frac{3\left(\frac{a_o}{W}\right)^{0.5}\left[1.99 - \left(\frac{a_o}{W}\right)\left(1 - \frac{a_o}{W}\right)\left(2.15 - \frac{3.93a_o}{W} + \frac{2.7{a_o}^2}{W^2}\right)\right]}{2\left(1 + \frac{2a_o}{W}\right)\left(1 - \frac{a_o}{W}\right)^{1.5}} \tag{3}$$

To facilitate the calculation of K_Q, values of $f\left(\frac{a}{W}\right)$ are given in Table 2 for specific values of $\frac{a_o}{W}$.

9.2.3.3 For compact specimens calculate K_Q using equation (4) [3].

$$K_Q = \frac{F_Q}{BW^{0.5}} \times f'\left(\frac{a_o}{W}\right) \tag{4}$$

where

$$f'\left(\frac{a_o}{W}\right) = \frac{\left(2 + \frac{a_o}{W}\right)\left(0.886 + 4.64\frac{a_o}{W} - 13.32\frac{a_o^2}{W^2} + 14.72\frac{a_o^3}{W^3} - 5.6\frac{a_o^4}{W^4}\right)}{\left(1 - \frac{a_o}{W}\right)^{1.5}} \tag{5}$$

To facilitate the calculation of K_Q, values of $f'\left(\frac{a_o}{W}\right)$ are given in Table 3 for specific values of $\frac{a_o}{W}$.

9.2.4 *Calculation of* K_{Ic}

Calculate the factor $2.5(K_Q/\sigma_{YS})^2$. If this is less than the crack length (a_o), thickness (B) and ligament ($W - a_o$), and all other criteria are met, then $K_{Ic} = K_Q$. If $2.5(K_Q/\sigma_{YS})^2$ is greater than any one or more of a_o, B or $W - a_o$, or if any of the other validity criteria are not satisfied, the K_{Ic} test is invalid, and only a K_Q value can be reported. In this case the test data shall be re-assessed to see if valid CTOD or J values can be determined according to **9.3** or **9.4** respectively.

9.3 Determination of CTOD

9.3.1 *Interpretation of the force* (F) *versus notch opening displacement* (V) *record*

NOTE The record will normally be one of the six types shown in Figure 13.

9.3.1.1 *Determination of* F_c *and* V_c*, or* F_u *and* V_u

Refer to Figure 13, record types (1) to (5), and the amount of Δa (see **8.7.3**). Measure and record the critical values of F_c and V_c, or F_u and V_u (as appropriate to the amount of Δa) from the test record at points corresponding to:

a) fracture, when there are no significant pop-ins (see **9.1**);

NOTE Examples of these critical forces and displacements are given in Figure 13 record types (1), (2) and (4).

b) the earliest significant pop-in prior to fracture [see Figure 13 record types (3) and (5)] or prior to the first attainment of a maximum force plateau for which the force drop d_n % F_1 equals or exceeds 5 % [see **9.1**, equation (1) and Figure 14];

c) fracture, when all significant pop-ins prior to fracture give values of d_n % F_1, that are less than 5 %.

9.3.1.2 *Determination of* F_m *and* V_m

Refer to Figure 13, record type (6). Where fracture or significant pop-ins having d_n % F_1 values equal to or greater than 5 % [see **9.1**, equation (1) and Figure 14] have not occurred prior to the first attainment of a maximum force plateau, measure and record the values of F_m and V_m from the test record at the point corresponding to the first attainment of the maximum force. (See **9.1**, note 2.)

9.3.1.3 *Determination of* V_p

Refer to Figure 16. Determine and record the plastic component of notch opening displacement (V_p) from the test record, i.e. corresponding to the appropriate notch opening displacement, V_c, V_u or V_m as determined in **9.3.1.1** and **9.3.1.2**.

Determine V_p either graphically or analytically. The graphical method is performed either manually from the test record, or using computer techniques. The analytical method is based on elastic compliance techniques, and involves subtracting the theoretical elastic notch opening displacement (V_e) from the appropriate total notch opening displacement.

NOTE When attached knife edges are used [see Figure 8(b) and Figure 9], the ratio of knife edge thickness to specimen width, z/W, may need to be taken into consideration in the elastic compliance relationship (see **8.1.4**).

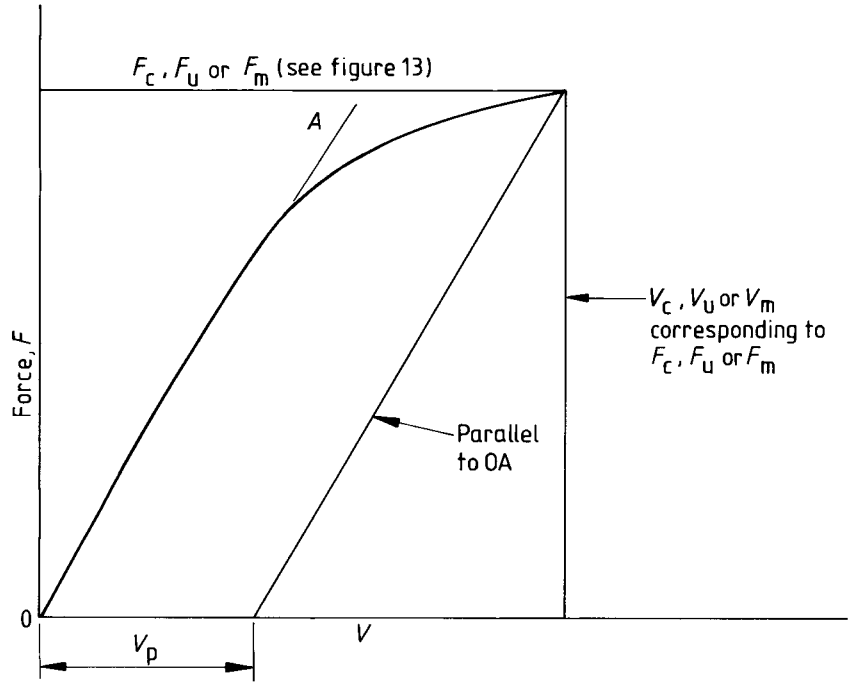


Figure 16 — Definition of V_p (for the determination of CTOD)

9.3.2 ***Calculation of CTOD***

9.3.2.1 *General*

Using the dimensions B, W, $(C - W)$ and z, (as determined in **8.1**), the dimension a_0 (as determined in **8.7.2**), the forces of F_c, F_u or F_m (as determined in **9.3.1**), and the corresponding value of V_p (as determined in **9.3.1.3**), calculate either δ_c using F_c, or δ_u using F_u, or δ_m using F_m, from the relationships given in **9.3.2.2** to **9.3.2.4**.

9.3.2.2 *Bend specimens*

For a bend specimen (see Figure 2 and Figure 3),

$$\delta = \left[\frac{FS}{BW^{1.5}} \times f\left(\frac{a_0}{W}\right)\right]^2 \frac{(1 - v^2)}{2\sigma_{YS}E} + \frac{0.4\,(W - a_0)\,V_p}{0.4W + 0.6a_0 + z} \qquad (6)$$

where S is the bending span (see **8.2**), and $f\left(\frac{a_0}{W}\right)$ is given by equation (3) in **9.2.3.2**, or by the values in Table 2 corresponding to specific values of $\frac{a_0}{W}$.

9.3.2.3 *Straight notch compact specimens*

For a straight notch compact specimen (see Figure 4),

$$\delta = \left[\frac{F}{BW^{0.5}} \times f'\left(\frac{a_0}{W}\right)\right]^2 \frac{(1 - v^2)}{2\sigma_{YS}E} + \frac{0.46\,(W - a_0)\,V_p}{0.46W + 0.54a_0 + (C - W) + z} \qquad (7)$$

where $f'\left(\frac{a_0}{W}\right)$ is given by equation (5) in **9.2.3.3**, or by the values in Table 3 corresponding to specific values of $\frac{a_0}{W}$.

9.3.2.4 *Stepped notch compact specimens*

For a stepped notch compact specimen (see Figure 5),

$$\delta = \left[\frac{F}{BW^{0.5}} \times f'\left(\frac{a_\mathrm{o}}{W}\right)\right]^2 \frac{(1 - v^2)}{2\sigma_\mathrm{YS}E} + \frac{0.46\,(W - a_\mathrm{o})\,V_\mathrm{p}}{0.46W + 0.54a_\mathrm{o} + z} \qquad (8)$$

where $f'\left(\frac{a_\mathrm{o}}{W}\right)$ is the same as in **9.3.2.3**.

9.4 Determination of J

9.4.1 *Interpretation of the force* (F) *versus load-line displacement* (q) *record*

NOTE The record will normally be one of the six types shown in Figure 13.

9.4.1.1 *Determination of* F_c *and* q_c, *or* F_u *and* q_u

Refer to Figure 13, record types (1) to (5), and the amount of Δa (see **8.7.3**). Measure and record the critical values of F_c and q_c, or F_u and q_u (as appropriate to the amount of Δa) from the test record at points corresponding to:

a) fracture, when there are no significant pop-ins (see **9.1**);

NOTE 1 Examples of these critical forces and displacements are given in Figure 13 for record types (1), (2) and (4).

b) the earliest significant pop-in prior to fracture or the first attainment of a maximum force plateau for which the force drop d_n % F_1 equals or exceeds 4 % for a bend specimen or 5 % for a stepped notch compact specimen [see **9.1**, equation (1), and Figure 14];

NOTE 2 Examples of these critical forces and displacements are given in Figure 13 for record types (3) and (5).

c) fracture, when all significant pop-ins prior to fracture give values of d_n % F_1 that are less than 4 % for a bend specimen and less than 5 % for a stepped notch compact specimen.

9.4.1.2 *Determination of* F_m *and* q_m

Refer to Figure 13, record type (6). Where fracture or significant pop-ins having d_n % F_1 values equal to or greater than 4 % in a bend specimen, or 5 % in a stepped notch compact specimen [see **9.1**, equation (1) and Figure 14] have not occurred prior to the first attainment of a maximum force plateau, measure and record the values of F_m and q_m from the test record at the point corresponding to the first attainment of the maximum force. (See **9.1**, note 2.)

9.4.1.3 *Determination of* U_p

Refer to Figure 17. Determine and record the plastic component of the work done (U_p), by measuring the area indicated in Figure 17, and corresponding to the appropriate load-line displacements q_c, q_u or q_m (as determined in **9.4.1.1** and **9.4.1.2**). The area corresponding to U_p in Figure 17 may be determined either directly from the test record (e.g. by using a polar planimeter), or by numerical integration by computer techniques, or by a combination of the latter and an analytical method based on elastic compliance, which involves the subtraction of the theoretical elastic area (U_e) from the total area (U).

NOTE When the analytical method is used, and the specimen has attached knife edges [see Figure 8(b) and Figure 9], the ratio of the knife edge thickness to specimen width, z/W, may need to be taken into consideration in the elastic compliance relationship (see **8.1.4**).

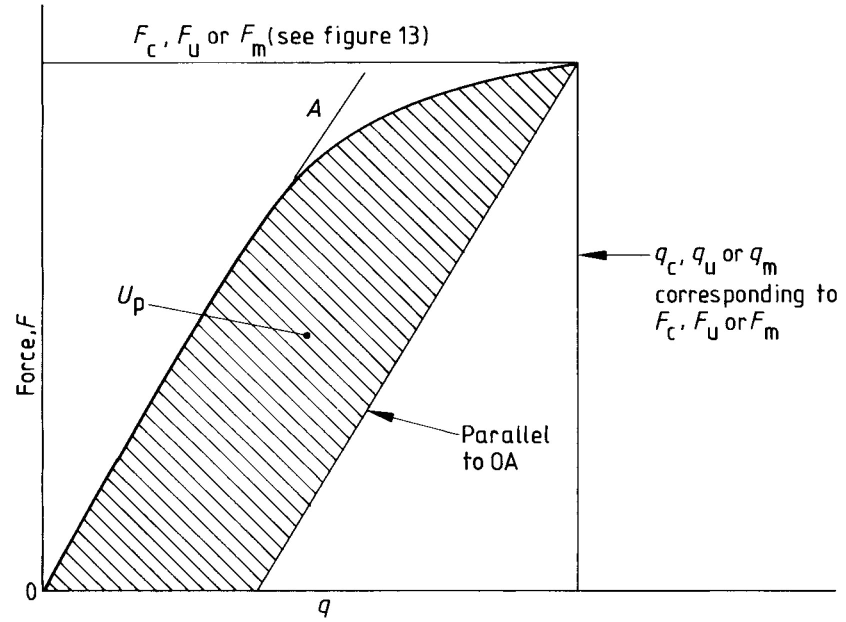


Figure 17 — Definition of U_p (for the determination of J)

9.4.2 *Calculation of J*

9.4.2.1 *General*

Using the dimensions B and W (as determined in **8.1**), the dimension a_o (as determined in **8.7.2**), the forces F_c, F_u or F_m (as determined in **9.4.1**), and the corresponding value of U_p (as determined in **9.4.1.3**), calculate either J_c using F_c, J_u using F_u, or J_m using F_m, from the relationships given in **9.4.2.2** and **9.4.2.3**.

9.4.2.2 *Bend specimens*

For a bend specimen (see Figure 2 and Figure 3),

$$J = \left[\frac{FS}{BW^{1.5}} \times f\left(\frac{a_o}{W}\right)\right]^2 \frac{(1 - v^2)}{E} + \frac{2U_p}{B(W - a_o)} \qquad (9)$$

where S is the bending span (see **8.2**), and $f\left(\frac{a_o}{W}\right)$ is given by equation (3) in **9.2.3.2**, or by values in Table 2 corresponding to specific values of $\frac{a_o}{W}$.

9.4.2.3 *Stepped notch compact specimens*

For a stepped notch compact specimen (see Figure 5),

$$J = \left[\frac{F}{BW^{0.5}} \times f'\left(\frac{a_o}{W}\right)\right]^2 \frac{(1 - v^2)}{E} + \frac{\eta_p U_p}{B(W - a_o)} \qquad (10)$$

where $f'\left(\frac{a_o}{W}\right)$ is given by equation (5) in **9.2.3.3**, or by the values in Table 3 corresponding to specific values of $\frac{a_o}{W}$ and η_p is equal to $2 + 0.522(1 - a_o/W)$[7].

---

[7] See ASTM Standard E 813-89.

10 Validity check lists

10.1 General

For a determination to be valid the requirements in **10.2** and **10.3** shall be complied with. Use of the check lists will enable an invalid determination to be abandoned at the earliest possible stage.

10.2 Specimen dimensions

10.2.1 Before fatigue precracking check that the specimen has the dimensions and tolerances specified in **5.1**.

10.2.2 Before carrying out the fracture test, check that:

a) the minimum surface crack length (a) is at least 0.45 of the specimen width (W);

b) both ends of the fatigue crack have extended for at least 1.3 mm or 2.5 % of the specimen width (W) from the root of the machined notch, whichever is the greater;

c) the difference between the two surface crack length measurements is not greater than 15 % of the average of these two measurements;

d) the fatigue precrack is within the appropriate envelope (see Figure 6) on both surfaces of the specimen;

e) the plane of the fatigue precrack is within 10° of the plane of crack extension.

10.2.3 After carrying out the fracture test, check that:

a) multi-plane fatigue precracking and fracture is not present at the fatigue precrack front;

b) the average crack length (a_0) to specimen width (W) ratio is between 0.45 and 0.55 (see **8.7.2**);

c) no two of the nine crack length measurements differ by more than 10 % a_0 (see note to **8.7.2**);

d) no part of the fatigue precrack front is closer to the crack starter notch than 1.3 mm or 2.5 % W, whichever is the larger;

e) the plane of the fatigue precrack is within 10° of the plane of crack extension.

10.3 Other items

Before starting to analyse the data in accordance with clause **9**, check that:

a) when a force versus displacement record is to be used for a manual analysis, the initial slope of the record is between 0.85 and 1.5 (see **8.6**);

b) the fatigue stress intensity factor (K_f) has not exceeded the limits given in **6.4.5** and **6.4.6**;

c) the fatigue ratio (R) does not exceed 0.1.

11 Test report

The test report shall show:

a) the number of this British Standard (i.e. BS 7448-1);

b) the identity of the test specimen;

c) the identity and form of the material tested (e.g. forging, plate, casting), and its condition (see **6.1**);

d) the geometry and main dimensions of the specimen tested (see clause **5** and **8.1**);

e) whether the specimen was full thickness or sub-size (see **5.1.2**);

f) the crack plane orientation (see **6.2**);

g) the fatigue precracking details, including the final F_f and R values (see **6.4.2** and **6.4.7**);

h) the tensile strength (σ_{TSP}) and 0.2 % proof strength (σ_{YSP}) of the specimen material at the temperature of fatigue precracking;

i) the span (S) used in a three-point bend test (see **8.2**), if applicable;

j) the knife edge thickness (z) (see **8.1.4**), if applicable;

k) the rate of increase in initial stress intensity factor ($\dot{K}$) (see **8.5**);

l) the force (F) versus notch opening displacement (V) record (see **8.6**), and/or the force (F) versus load-line displacement (q) record, (see **8.6**);

m) the temperature (T) of the specimen at the time of the test (see **8.4**);

n) the 0.2 % proof strength (σ_{YS}) of the specimen at the temperature of the test;

o) a diagram of the fracture surface showing the crack length (a_o) and the shape and size of the fatigue precrack, the extent of stable crack extension (Δa), and any evidence of arrested brittle crack extension associated with pop-in behaviour, or any other unusual features of the fracture surface (see **8.7**);

p) the value of the plane strain fracture toughness (K_{Ic}), or the corresponding invalid quantity (K_Q), including the value of F_{max}/F_Q (see **9.2.2**), if applicable;

q) the value and type of CTOD (e.g. δ_c, δ_u or δ_m), if applicable;

r) the value and type of J (e.g. J_c, J_u or J_m), if applicable;

s) details of any of the above items that fail to meet the validity requirements in the stated clauses, and thereby result in an invalid determination of fracture toughness according to this method.

Appendix A
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4. DAWES. M.G. Elastic-plastic fracture toughness based on the COD and J-contour integral concepts. *In: Symposium on elastic-plastic fracture,* 1977, ASTM Special Technical Publication 668, p307.

5. WILLOUGHBY, A.A. and S.J. GARWOOD. On the unloading compliance method of deriving a single-specimen R-curve in three-point bending. *In 2nd Symposium on elastic-plastic fracture,* 1983, ASTM Special Technical Publication 803, vol. 2 p372.

Appendix B
Crack plane identification

The system of crack plane identification described in this appendix shall be used in order to avoid ambiguous interpretation. It is based on an arrangement of three reference axes related to the main stressing direction which are as follows:

X is longitudinal, i.e. parallel to the grain flow;

Y is transverse, i.e. normal to the X and Z axes;

Z is short transverse e.g. coincident with the thickness direction.

Using a two-letter code, the first letter indicates the direction perpendicular to the crack plane and the second the direction of crack front movement. Thus X-Z represents a crack in a longitudinal specimen moving in a short transverse direction. Figure 18 shows the system applied to a rectangular section.

In order to identify crack planes in cylindrical sections the same code system shall be applied. This system is illustrated in Figure 19.

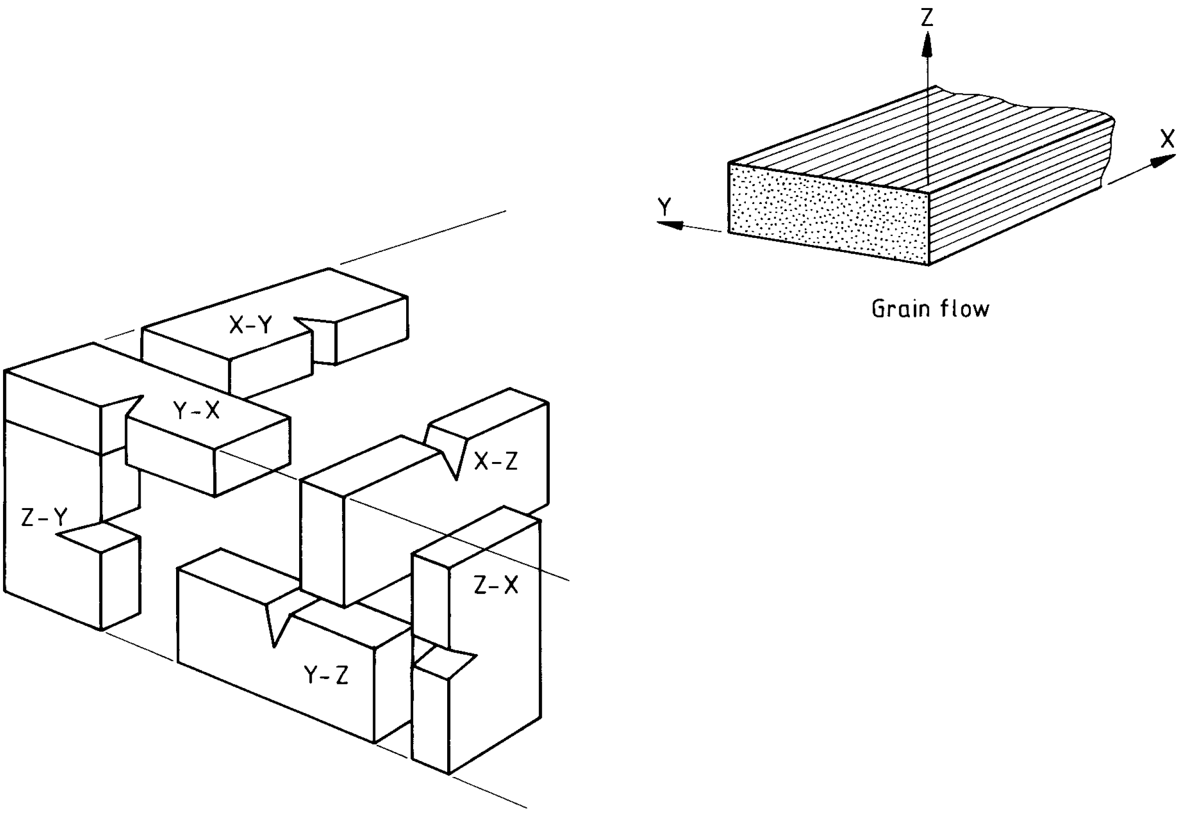
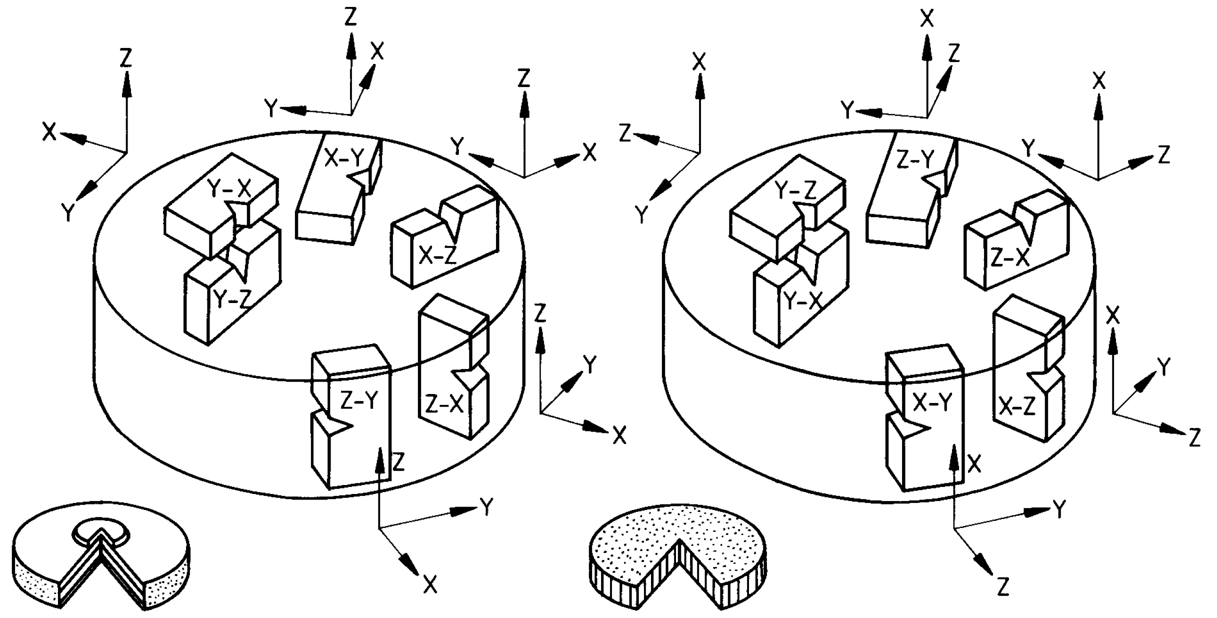


Figure 18 — Basic fracture plane identification: rectangular section



(a) Radial grain flow, axial working direction (b) Axial grain flow, radial working direction

Figure 19 — Basic fracture plane identification: cylindrical sections

Cracks moving in planes not coincident with two of the reference axes shall be similarly referenced. When the plane of the crack is coincident with a primary reference with direction of propagation at an angle to the other two, the combination can be written X-YZ where the specimen is longitudinal and the direction transverse/short transverse. Similarly a skewed plane but primary direction could be represented by YZ-X. Examples are shown in Figure 20.

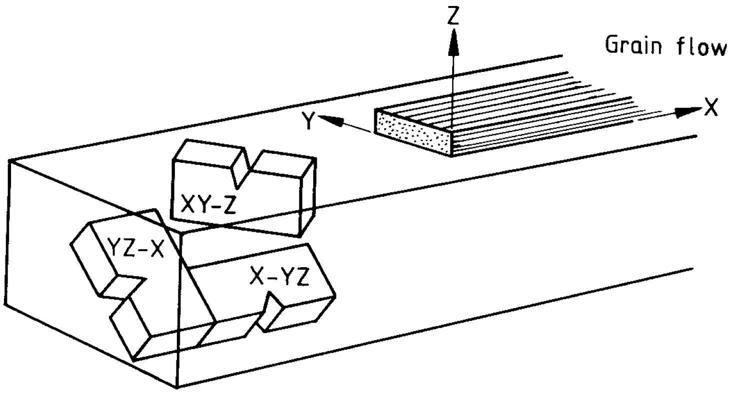


Figure 20 — Non-basic fracture plane identification

Appendix C
Measurement of load-line displacement (*q*) in a three point bend test

As described in **9.4**, the method of calculating critical *J* values requires the measurement of the area under a force (*F*) versus load-line displacement (*q*) record (see Figure 17). However, unlike the situation when testing a stepped notch compact specimen (see Figure 5 and **8.3**), it is difficult to obtain direct measurements of load-line displacement for a three-point bend specimen (see Figure 2 and Figure 3 and **8.2**). The difficulty is in separating the true load-line displacements of the specimen from the elastic plastic displacements in the specimen under the three loading points, and also the elastic displacements in the loading fixtures and testing machine. These extraneous displacements are additive, so that measurements of machine ram or crosshead displacement, or relative displacements between the specimen and testing machine will overestimate the true load-line displacement. The extent of such an overestimate will vary with the specimen material, condition and temperature, the loading rate, and also the dimensions of the specimen, loading fixtures and testing machine.

The only way to obtain load-line displacement directly, is to measure the relative movement of appropriate points on the specimen. This can be done for example, by measuring the vertical displacement of the notch tip relative to a horizontal line that is a fixed distance from the undeformed edge of the specimen near the outer loading points. This type of direct measurement may be obtained by using a horizontal “comparator” bar [4], and measuring the vertical displacement of the bar relative to the notch tip, or notch mouth as shown schematically in Figure 21.

NOTE Measurements to the notch mouth (see Figure 21) represent the load-line displacement (*q*) to an accuracy of better than ±2 % for q_m equal to or less than $0.14W$, which corresponds to a total notch opening angle of 8°.

An indirect measurement of load-line displacement may be obtained by measuring the extraneous displacements separately, and then subtracting them from the machine crosshead displacement. Thus, referring to the measurements in Figure 22, it can be seen that the load-line displacement at any particular force (*F*) will be given by $q = \Delta - \Delta_1 - \Delta_2$. If preferred, the total extraneous displacement ($\Delta_1 + \Delta_2$) can be measured with the loading points close together, as shown in Figure 23.

An alternative indirect measurement of load-line displacement may be obtained from two measurements of notch opening displacement. For example, using one notch opening displacement gauge located near the notch mouth, and a second located above the notch mouth (see Figure 24), the load-line displacement may be determined from the following equation [5]:

$$q = \frac{W(V_2 - V_1)}{z_2 - z_1}$$

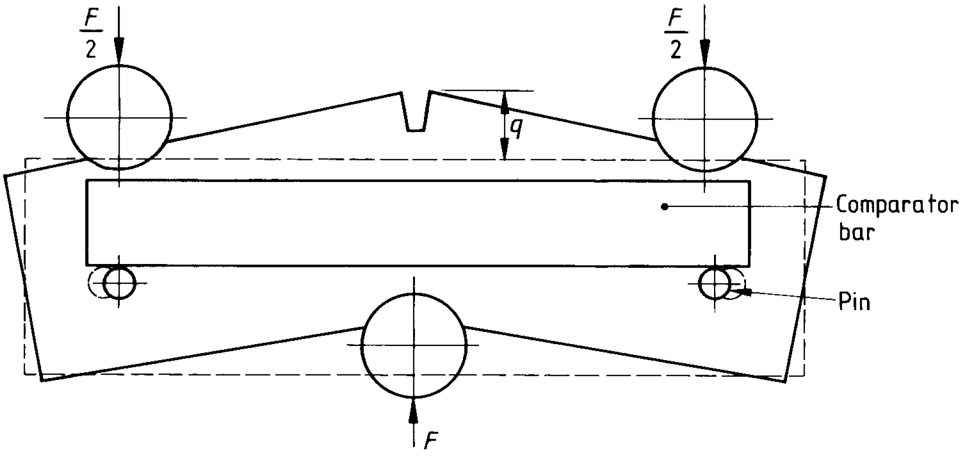
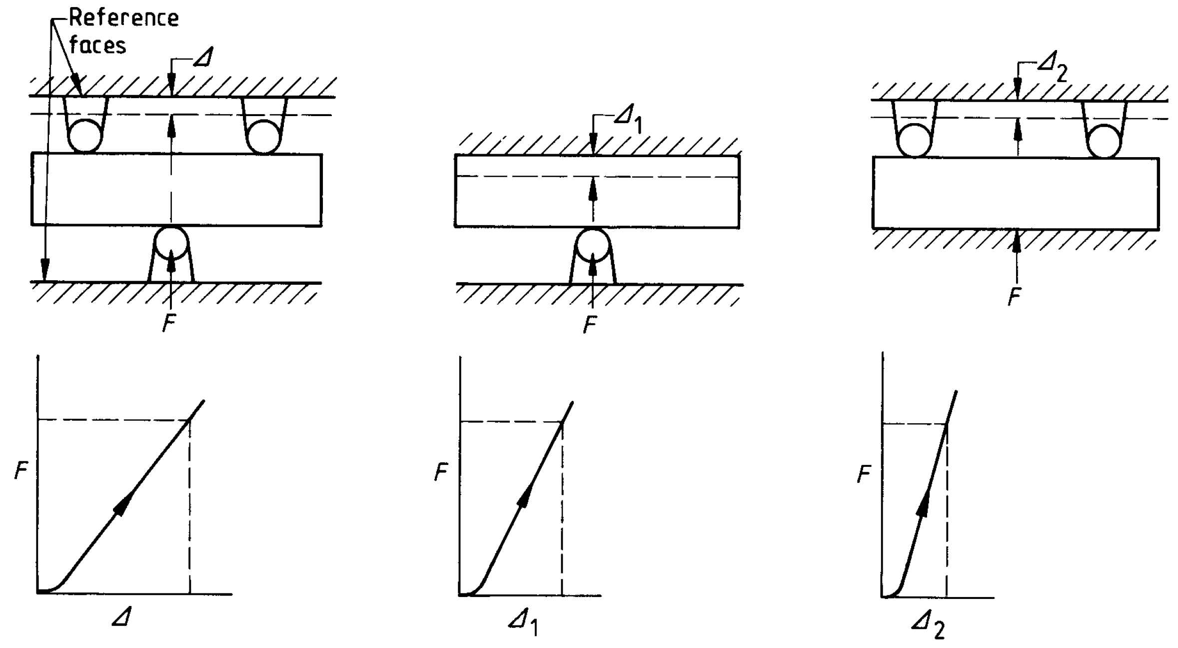


Figure 21 — Principle of the “comparator” bar measurement



(a) Crosshead displacement, Δ

(b) Elastic plastic indentation of specimen and compression of central roller and anvil, Δ_1

(c) Elastic plastic indentation of specimen and compression of outer rollers and anvils, Δ_2

Figure 22 — Displacements associated with three point bend specimens

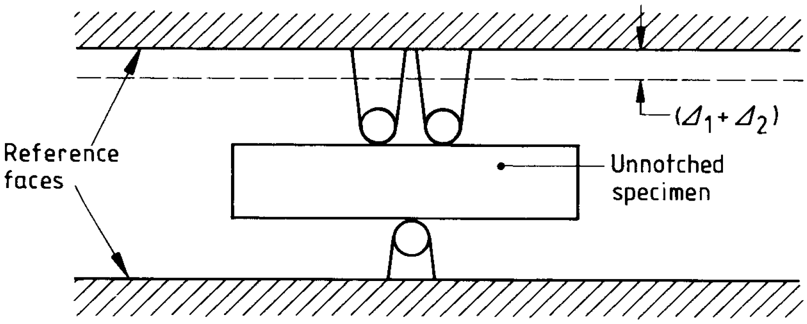


Figure 23 — Simultaneous determination of extraneous displacements ($\Delta_1 + \Delta_2$)

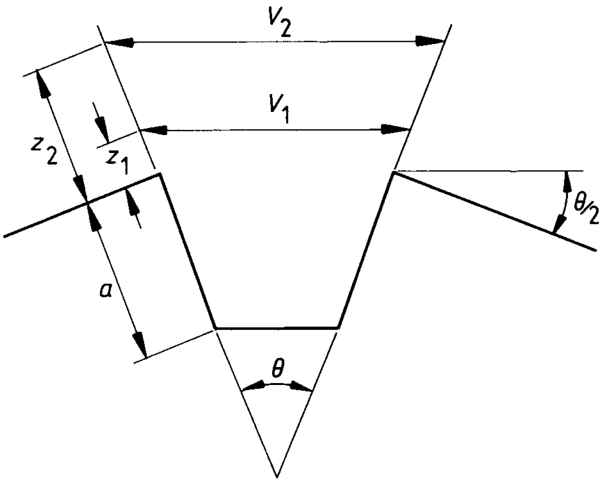


Figure 24 — Location of two notch opening displacement measurements (V_1 and V_2) for the determination of load-line displacement

Publication(s) referred to

BS 427, *Method for Vickers hardness test and for verification of Vickers hardness testing machines.*

BS 1610, *Materials testing machines and force verification equipment.*

BS 1610-1, *Specification for the grading of the forces applied by materials testing machines.*

BS 3846, *Methods for calibration and grading of extensometers for testing of metals.*

BS 7448, *Fracture mechanics toughness tests.*

BS 7448-3, *Methods for determining dynamic* K_{Ic}*, critical CTOD and critical J values of metallic materials.*[8]

BS EN ISO 12737, *Metallic materials — Determination of plane-strain fracture toughness.*

ASTM E 813:89, *Standard test method for* J_{Ic}*, a measure of fracture toughness.*

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[8] In preparation.

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