

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
British Railways Board
British Steel Industry
Copper Development Association
Department of Trade and Industry (National Engineering Laboratory)
Department of Trade and Industry (National Measurement Accreditation Service)
Department of Trade and Industry (National Physical Laboratory)
ERA Technology Ltd.
GAMBICA (BEAMA Ltd.)
Ministry of Defence
Society of British Aerospace Companies Limited
Welding Institute

The following bodies were also represented in the drafting of the standard, through subcommittees and panels:

BCIRA
BEAMA Ltd.
Electricity Supply Industry in United Kingdom
Lloyd's Register of Shipping
Steel Casting Research and Trade Association
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

© BSI 27 February 2002

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

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.

ISBN 0 580 20037 X

Contents

	Page
Committees responsible	Inside front cover
Foreword	iii
1 Scope	1
2 Definitions	1
3 Symbols and designations	2
4 Principle	4
5 Test specimens	4
6 Specimen preparation and fatigue precracking	9
7 Test equipment	18
8 Test procedure	22
9 Analysis of test data	25
10 Validity check lists	32
11 Test report	33
Appendix A Bibliography	34
Appendix B Crack plane identification	34
Appendix C Measurement of load-line displacement (q) in a three point bend test	37
Figure 1 — Flow chart for choice of fracture toughness parameter, specimen design and displacement measurement	5
Figure 2 — Proportional dimensions and tolerances for a rectangular section bend specimen	6
Figure 3 — Proportional dimensions and tolerances for a square section bend specimen	6
Figure 4 — Proportional dimensions and tolerances for a straight notch compact specimen	7
Figure 5 — Proportional dimensions and tolerances for a stepped notch compact specimen	8
Figure 6 — Acceptable fatigue crack starter notches and fatigue crack configurations	10
Figure 7 — Chevron notch	11
Figure 8 — Outward pointing knife edges and corresponding notch geometries	12
Figure 9 — Inward pointing knife edges and corresponding notch geometries	13
Figure 10 — Fixture for three point bend tests	14
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 $0.24W - 0.005W$, $- 0.015W$	20
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 $0.24W + 0.000W$, $- 0.005W$	21
Figure 13 — Characteristic type of force versus displacement records in fracture tests	23
Figure 14 — Assessment of pop-in behaviour	26
Figure 15 — Definition of F_Q (for the determination of K_Q)	27
Figure 16 — Definition of V_p (for the determination of CTOD)	29
Figure 17 — Definition of U_p (for the determination of J)	31
Figure 18 — Basic fracture plane identification: rectangular section	35
Figure 19 — Basic fracture plane identification: cylindrical sections	36
Figure 20 — Non-basic fracture plane identification	36

	Page
Figure 21 — Principle of the “comparator” bar measurement	37
Figure 22 — Displacements associated with three point bend specimens	38
Figure 23 — Simultaneous determination of extraneous displacements ($\Delta_1 + \Delta_2$)	38
Figure 24 — Location of two notch opening displacement measurements (V_1 and V_2) for the determination of load-line displacement	39
Table 1 — Dimensions of specimens that may lead to valid K_{Ic} values	9
Table 2 — Values of $f\left(\frac{a_o}{W}\right)$ for three point bend specimens	16
Table 3 — Values of $f'\left(\frac{a_o}{W}\right)$ for compact specimens	18
Publication(s) referred to	40

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 toughness²⁾;*
- *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.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

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.

The BSI copyright notice displayed throughout this document indicates when the document was last issued.

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.

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⁾

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

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.

<i>a</i>	nominal crack length (see Figure 2 to Figure 6) <i>or</i> , for the purposes of fatigue precracking (see 6.4.5 and 6.4.6), an assumed value $\leq a_0$
a_0	average original crack length (see 8.7.2)
<i>B</i>	specimen thickness
<i>C</i>	total width of compact specimen
<i>E</i>	Young's modulus of elasticity at the temperature of interest
<i>f</i>	a mathematical function of $\left(\frac{a}{W}\right)$ or $\left(\frac{a_0}{W}\right)$ for bend specimens
<i>f'</i>	a mathematical function of $\left(\frac{a}{W}\right)$ or $\left(\frac{a_0}{W}\right)$ for compact specimens
<i>F</i>	applied force
F_d	particular value of <i>F</i> , 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 <i>F</i> , 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
<i>J</i>	experimental equivalent of the crack tip <i>J</i> -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
ν	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

^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 $\pm 2^\circ$.

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).

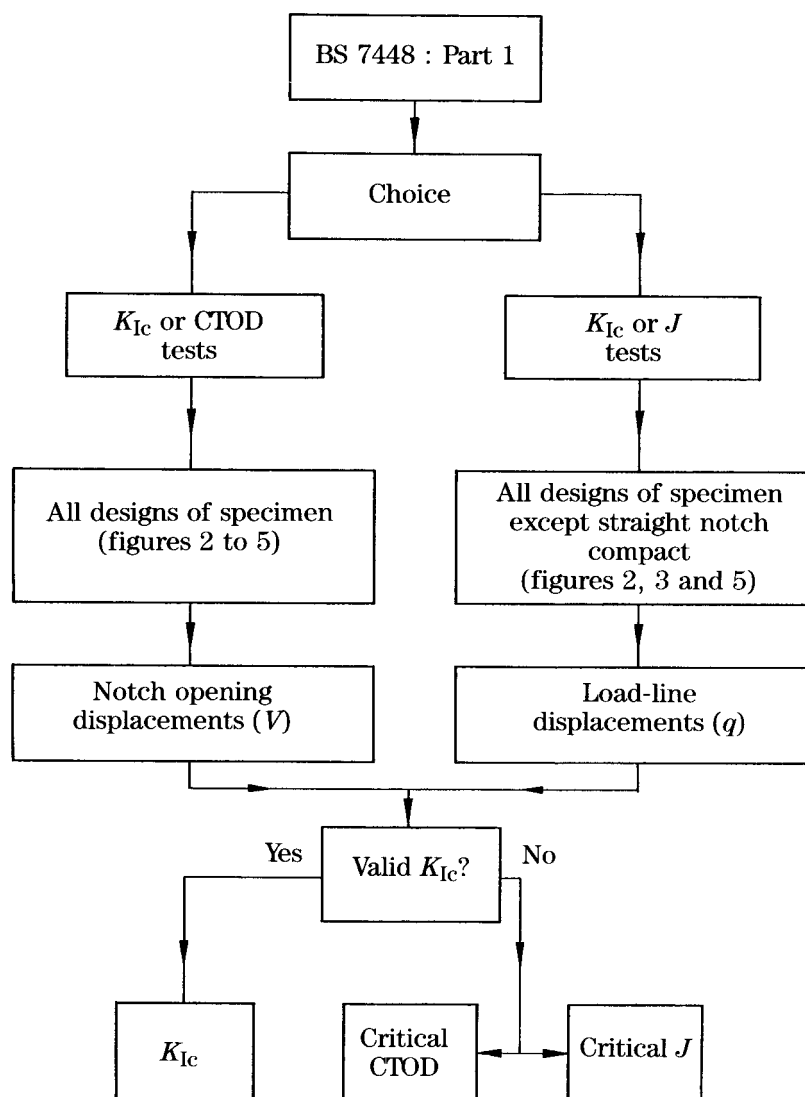
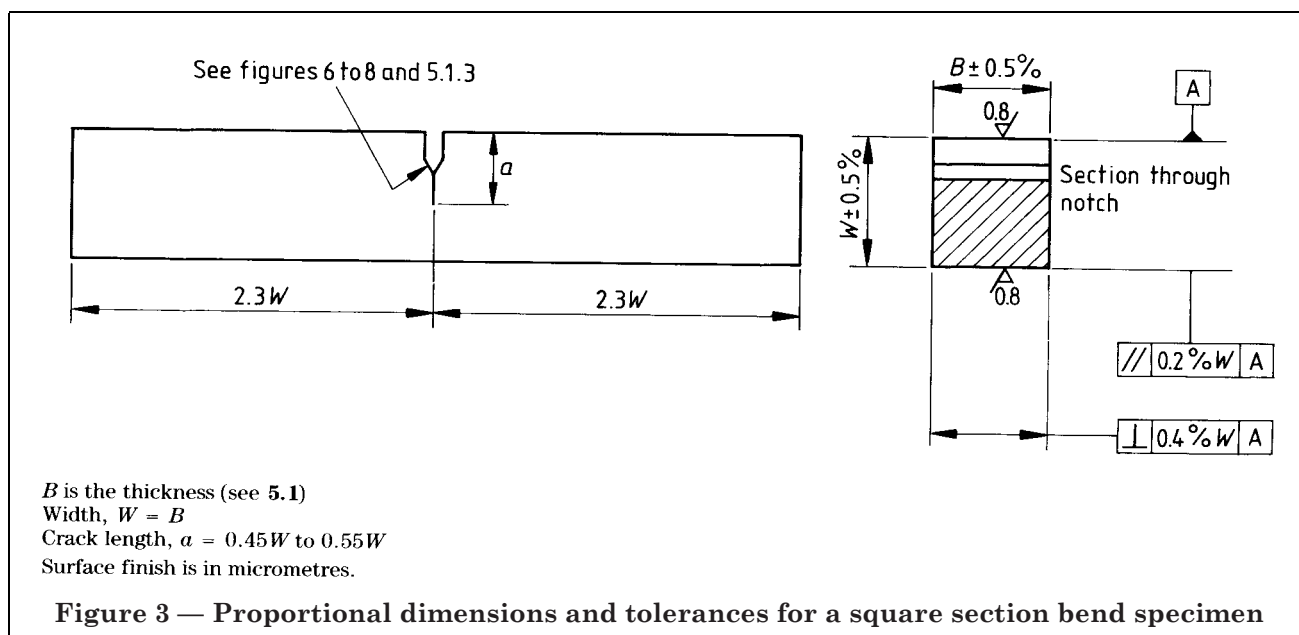
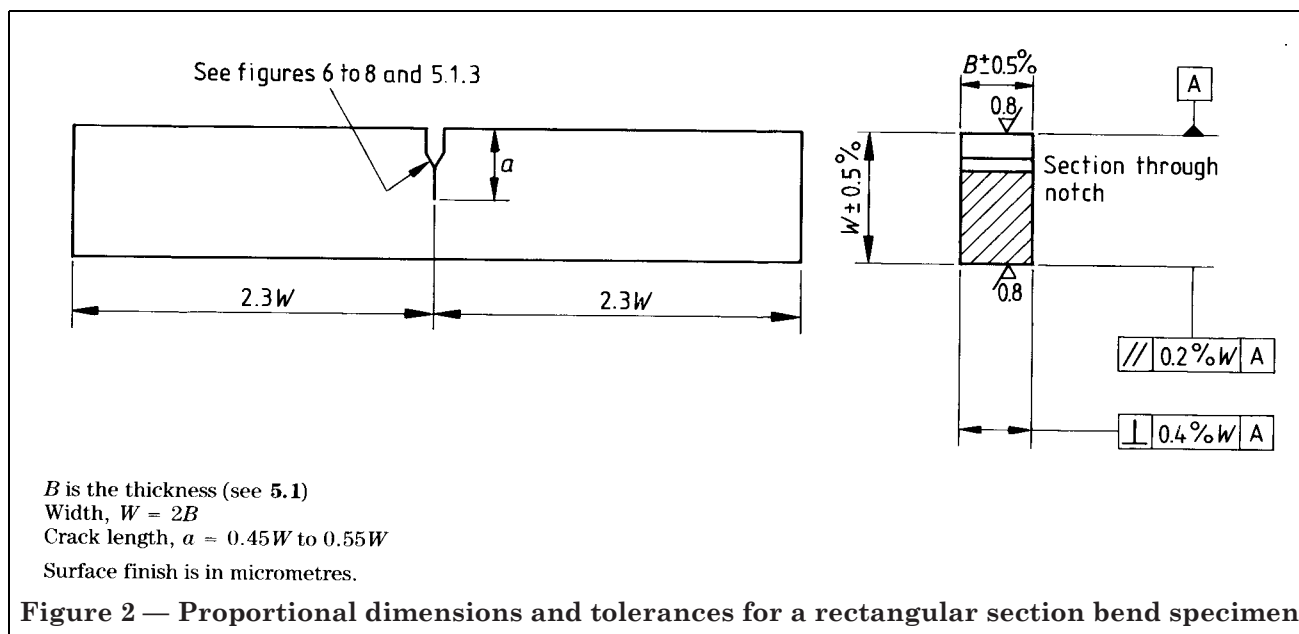
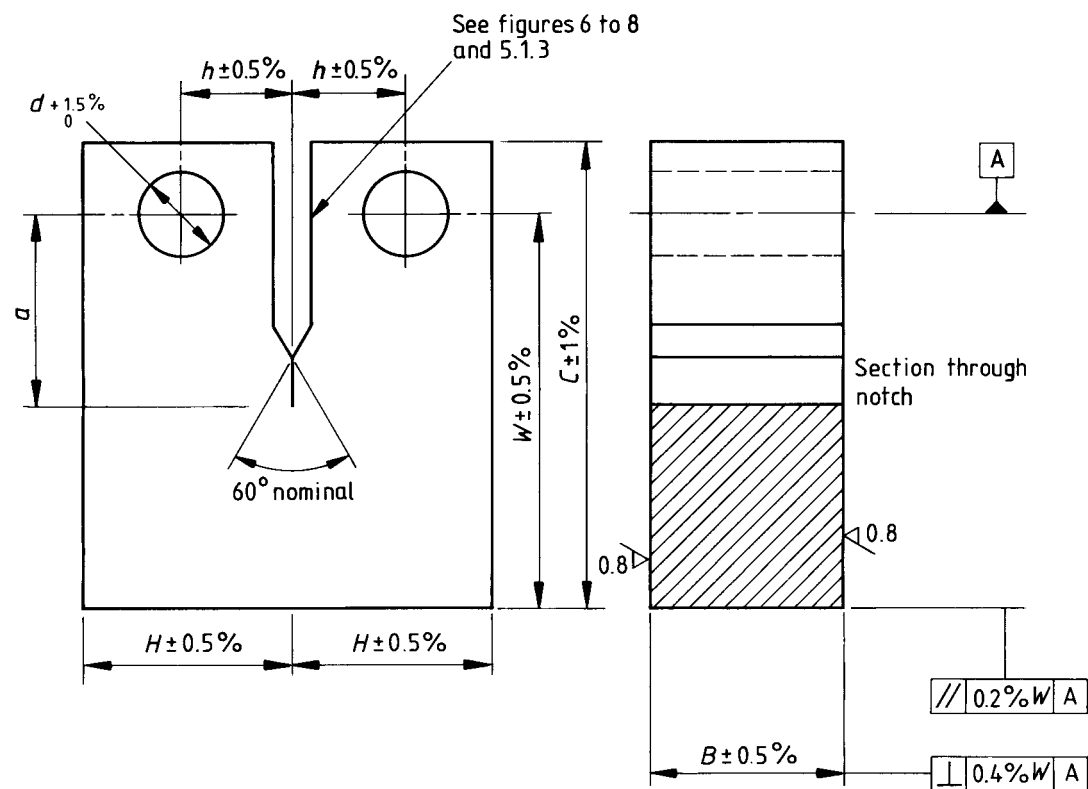


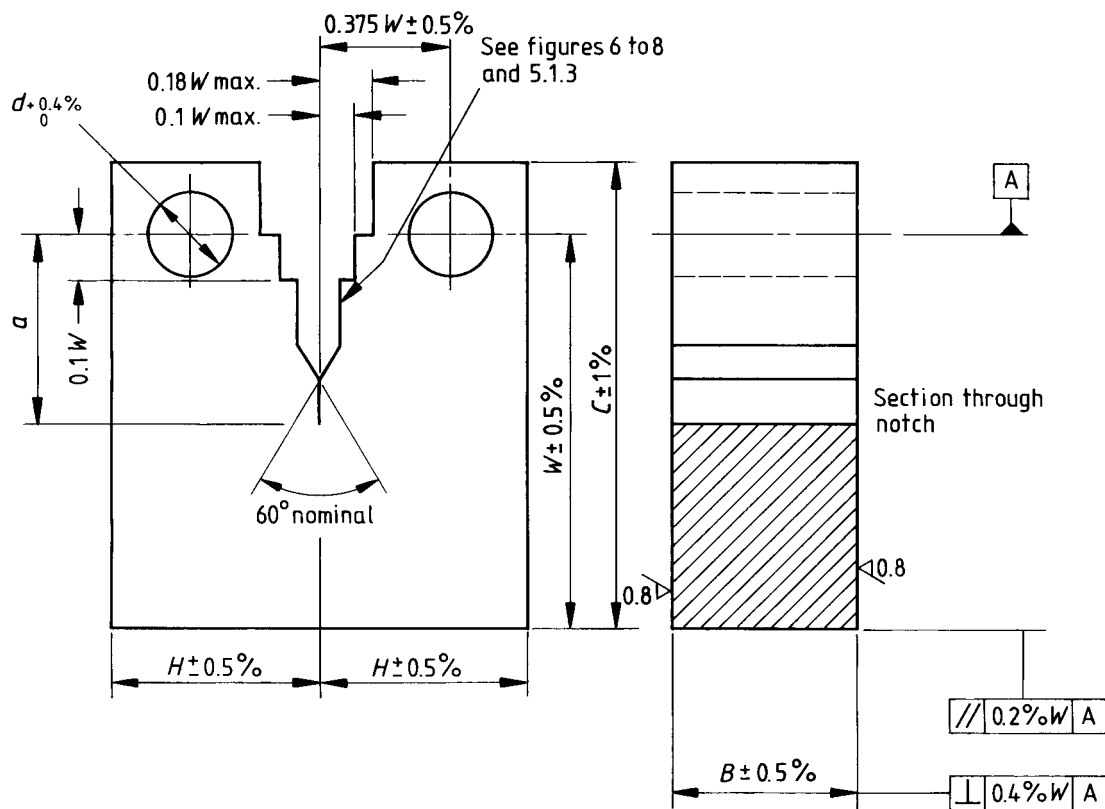
Figure 1 — Flow chart for choice of fracture toughness parameter, specimen design and displacement measurement





B is the thickness
 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:

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

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:

- an estimate of the K_{Ic} of the material; or
- 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

$\frac{\sigma_{YS}}{E}$		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.