

# Fracture mechanics toughness tests —

**Part 3: Method for determination of  
fracture toughness of metallic materials  
at rates of increase in stress intensity  
factor greater than  $3.0 \text{ MPa} \cdot \text{m}^{0.5} \text{ s}^{-1}$**

ICS 77.040.10

# Committees responsible for this British Standard

This British Standard was entrusted by Technical Committee ISE/NFE/4, Mechanical testing of materials, to Subcommittee ISE/NFE/4/4, Toughness testing, upon which the following bodies were represented:

- British Non-Ferrous Metals Federation
- GAMBICA Limited
- HSE — Health and Safety Executive
- Lloyd’s Register
- National Physical Laboratory
- Network Rail
- QinetiQ
- Society of British Aerospace Companies Ltd.
- UK Steel Association
- United Kingdom Accreditation Service
- Welding Institute

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# Contents

|                                                                                                                                                                                                | Page               |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Committees responsible                                                                                                                                                                         | Inside front cover |
| Foreword                                                                                                                                                                                       | iii                |
| 1 Scope                                                                                                                                                                                        | 1                  |
| 2 Normative references                                                                                                                                                                         | 1                  |
| 3 Terms and definitions                                                                                                                                                                        | 1                  |
| 4 Symbols and designations                                                                                                                                                                     | 3                  |
| 5 Principle                                                                                                                                                                                    | 5                  |
| 6 Test specimens                                                                                                                                                                               | 7                  |
| 7 Specimen preparation and fatigue precracking                                                                                                                                                 | 15                 |
| 8 Test equipment                                                                                                                                                                               | 17                 |
| 9 Test procedure                                                                                                                                                                               | 21                 |
| 10 Analysis of test data                                                                                                                                                                       | 24                 |
| 11 Check lists for qualification of data                                                                                                                                                       | 38                 |
| 12 Test report                                                                                                                                                                                 | 38                 |
| Figure 1 — Flow chart for the choice of fracture toughness parameter, specimen design and displacement measurement                                                                             | 6                  |
| Figure 2 — Proportional dimensions and tolerances for the rectangular section bend specimen                                                                                                    | 7                  |
| Figure 3 — Proportional dimensions and tolerances for the square section bend specimen                                                                                                         | 8                  |
| Figure 4 — Proportional dimensions and tolerances for the straight notch compact specimen                                                                                                      | 9                  |
| Figure 5 — Proportional dimensions and tolerances for the stepped notch compact specimen                                                                                                       | 10                 |
| Figure 6 — Acceptable fatigue crack starter notches and fatigue crack configurations                                                                                                           | 12                 |
| Figure 7 — Chevron notch                                                                                                                                                                       | 12                 |
| Figure 8 — Outward pointing knife edges and corresponding notch geometrics                                                                                                                     | 13                 |
| Figure 9 — Outward pointing knife edges and corresponding notch geometrics                                                                                                                     | 14                 |
| Figure 10 — Fixture for three point bend tests                                                                                                                                                 | 19                 |
| 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 $(0.24 \pm_{0.015}^{0.005}) W$      | 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 $(0.24 \pm_{0.005}^{+0.000}) W$ | 21                 |
| Figure 13 — Characteristic types of force versus displacement records in fracture tests                                                                                                        | 23                 |
| Figure 14 — Assessment of pop-in behaviour                                                                                                                                                     | 25                 |
| Figure 15 — Principal types of force versus crack mouth opening gauge displacement records showing the limits of allowable force and displacement variation for $K_{Ic}$ determination         | 27                 |
| Figure 16 — Force variation limits for fracture toughness determination                                                                                                                        | 28                 |
| Figure 17 — Limits of crack mouth opening gauge displacement variations for plane strain fracture toughness determination                                                                      | 29                 |
| Figure 18 — Definition of $V_p$ (for determination of CTOD)                                                                                                                                    | 30                 |
| Figure 19 — Limits of force and displacement for CTOD and J determination                                                                                                                      | 31                 |
| Figure 20 — Force and load point displacement variation for fracture toughness determination                                                                                                   | 33                 |

|                                                                                                                                          | Page |
|------------------------------------------------------------------------------------------------------------------------------------------|------|
| Figure 21 — Displacement variation limits for CTOD and $J$ determination                                                                 | 34   |
| Figure 22 — Definition of $U_p$ (for determination of $J$ )                                                                              | 35   |
| Figure A.1 — Resistance strain gauge positions for load measurements from rectangular section bend specimen                              | 41   |
| Figure A.2 — Limits of loading point displacement variations for CTOD and $J$ determination                                              | 42   |
| Figure B.1 — Schematic representation of the comparator bar                                                                              | 44   |
| Figure B.2 — Displacements associated with three-point bend specimens                                                                    | 44   |
| Figure B.3 — Simultaneous determination of extraneous displacements ( $z_2 - z_1$ )                                                      | 45   |
| Figure B.4 — Location of two notch opening displacement measurements ( $V_1$ and $V_2$ ) for the determination of load-line displacement | 45   |
| Figure C.1 — Basic fracture plane identification — Rectangular section                                                                   | 46   |
| Figure C.2 — Basic fracture plane identification — Cylindrical sections                                                                  | 46   |
| Figure C.3 — Non-basic fracture plane identification                                                                                     | 47   |
| Figure D.1 — Examples of good and unacceptable force records                                                                             | 48   |
| Figure D.2 — Examples of good and unacceptable notch opening displacement records                                                        | 48   |
| Figure D.3 — Test system for d.c. signal conditioners and amplifiers                                                                     | 49   |
| Figure D.4 — Example of the amplitude output of an instrument as a function of frequency                                                 | 49   |
| Figure D.5 — Test system for a.c. transducers                                                                                            | 50   |
| Figure E.1 — Force versus time record from dynamic tensile test showing no distinct yield point                                          | 52   |
| Figure E.2 — Force versus time record from dynamic tensile test showing distinct yield point                                             | 53   |
| Figure E.3 — Limits to ram displacement versus time record from dynamic tensile test                                                     | 53   |
| Table 1 — Dimensions of specimens that can lead to valid $K_{Ic}$ values                                                                 | 11   |
| Table 2 — Values of for $f\left(\frac{a}{W}\right)$ three point bend specimens                                                           | 16   |
| Table 3 — Values of for $f'\left(\frac{a}{W}\right)$ three point bend specimens                                                          | 17   |

## Foreword

This part of BS 7448 has been prepared by Technical Committee ISE/NFE/4. It is required because the instrumentation and procedures in BS 7448-1 may not be adequate for high rate tests.

This British Standard supersedes BS 6729:1987 which is withdrawn.

This part of BS 7448 is one of a series dealing with fracture mechanics toughness tests, the other parts being:

- *Part 1: Fracture mechanics toughness tests — Method for determination of  $K_{Ic}$  critical CTOD and critical  $J$  values of metallic materials.*
- *Part 2: Fracture mechanics toughness tests — Method for determination of  $K_{Ic}$ , critical CTOD and critical  $J$  values of welds in metallic materials.*
- *Part 4: Fracture mechanics toughness tests — Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials.*

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

This British Standard describes methods of test only, and should not be used or quoted as a specification. References to this standard should indicate that the methods of test used are in accordance with BS 7448-3:2005.

**CAUTION** 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.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

**Compliance with a British Standard cannot confer immunity from legal obligations.**

## Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, a blank page, pages 1 to 55 and a back cover.

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## 1 Scope

This part of BS 7448 describes 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 tested in displacement control at rates of increase in stress intensity factor greater than  $3.0 \text{ MPa} \cdot \text{m}^{0.5} \text{ s}^{-1}$  but less than  $3\,000 \text{ MPa} \cdot \text{m}^{0.5} \text{ s}^{-1}$  during the initial elastic deformation. Stress intensity factors greater than  $3\,000 \text{ MPa} \cdot \text{m}^{0.5} \text{ s}^{-1}$  are covered in Annex A. These rates are greater than those permitted in BS 7448-1.

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

NOTE This standard does not cover integrity assessments. Such assessments are covered in BS 7910.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS 7448-4:1997, *Fracture mechanics toughness tests — Part 4: Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials*.

BS 7935-1, *Constant amplitude dynamic force calibration — Part 1: Calibration and verification of non-resonant uniaxial dynamic testing systems — Method*.

BS 7935-2, *Constant amplitude dynamic force calibration — Part 2: Calibration of the calibration device instrumentation to be used for the dynamic calibration of non-resonant uniaxial dynamic testing systems — Method*.

BS EN ISO 7500-1:1999, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*.

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

## 3 Terms and definitions

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

### 3.1

#### stress intensity factor

$K$

magnitude of the stress field near the crack tip (a stress-field singularity) (see 3.2) in a homogeneous, ideally linear-elastic body

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

### 3.2

#### opening mode

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

### 3.3

#### plane strain fracture toughness

$K_{Ic}$

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

### 3.4

#### maximum fatigue stress intensity factor

$K_f$

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

1)  $1 \text{ N} \cdot \text{mm}^{-1.5} = 0.0316 \text{ MPa} \cdot \text{m}^{0.5} = 0.0316 \text{ MN} \cdot \text{m}^{1.5}$ .

**3.5**

**crack tip opening displacement**

**CTOD**

displacement of the crack surfaces normal to the original (undeformed) crack plane at the tip of the fatigue precrack, expressed in millimetres

**3.6**

**critical CTOD**

value of CTOD associated with a particular type of crack extension

**3.7**

***J*-integral**

mathematical expression, 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, expressed in  $\text{J/mm}^2$

NOTE  $1 \text{ J/mm}^2 = 1 \text{ MJ/m}^2 = 1 \text{ N/mm}$ .

**3.8**

***J***

experimental equivalent of the *J*-integral

**3.9**

**critical *J***

particular value of *J*

**3.10**

**brittle crack extension**

abrupt crack extension which occurs with or without prior stable crack extension (see 3.11)

**3.11**

**stable crack extension**

slow stable crack extension that includes the stretch zone width (see 3.12)

**3.12**

**stretch zone width**

**SZW**

length of crack extension that occurs during crack tip blunting; that is, prior to the onset of brittle crack extension, pop-in (see 3.13) or slow stable crack extension.

NOTE The SZW is [measured] in the same plane as the fatigue precrack.

**3.13**

**pop-in**

discontinuity in the force versus displacement record

NOTE A pop-in corresponds to a sudden increase in displacement, and, generally, a sudden decrease in force. Subsequently, the displacement and force increase to above their respective values at pop-in.

## 4 Symbols and designations

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

|                   |                                                                                                                                                                                                                               |
|-------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $a$               | crack length or, for the purposes of fatigue precracking (see 7.4.4 and 7.4.5), an assumed value $\leq a_o$ , in millimetres                                                                                                  |
| $a_o$             | average original crack length (see 9.7.1), in millimetres                                                                                                                                                                     |
| $B$               | specimen thickness, in millimetres                                                                                                                                                                                            |
| $B_N$             | net specimen thickness between sidegroove tips, in millimetres                                                                                                                                                                |
| $C$               | total width of compact specimen, in millimetres                                                                                                                                                                               |
| $D$               | ram displacement in dynamic tensile test, in millimetres                                                                                                                                                                      |
| $\dot{D}$         | ram displacement rate in dynamic tensile test, in millimetres per second                                                                                                                                                      |
| $E$               | Young's modulus of elasticity at the temperature of interest, in GPa                                                                                                                                                          |
| $f$               | a mathematical function of $(a/W)$ or $(a_o/W)$ for bend specimens                                                                                                                                                            |
| $f^*$             | a mathematical function of $(a/W)$ or $(a_o/W)$ for compact specimens                                                                                                                                                         |
| $f_1$             | electrical frequency at which the output signal amplitude is reduced by 10 %, in hertz                                                                                                                                        |
| $f_2$             | electrical frequency at which the output signal amplitude is reduced by 30 %, in hertz                                                                                                                                        |
| $F$               | applied force, in kilonewtons                                                                                                                                                                                                 |
| $\dot{F}$         | rate of change of applied force with time, in kilonewtons per second                                                                                                                                                          |
| $F_c$             | applied force at the onset of brittle crack extension or pop-in when $\Delta a$ is less than 0.2 mm, in kilonewtons                                                                                                           |
| $F_e$             | applied force at which permanent plastic deformation is first observed in dynamic tensile test, in kilonewtons                                                                                                                |
| $F_f$             | maximum fatigue precracking force during the final stages of fatigue crack extension (see 7.4.4 and 7.4.5), in kilonewtons                                                                                                    |
| $F_m$             | applied force at the first attainment of a maximum force plateau for fully plastic behaviour, in kilonewtons                                                                                                                  |
| $F_r$             | applied force at intersection of force versus displacement record in dynamic tensile test with 0.2 % offset line, in kilonewtons                                                                                              |
| $F_u$             | applied force at the onset of brittle crack extension or pop-in when the event is preceded by $\Delta a$ equal to or greater than 0.2 mm, in kilonewtons                                                                      |
| $F_A$             | applied force (in kilonewtons) at which the nominal stress equals:<br>$\frac{B\sigma_{\text{USD}}(W - a_o)^2}{S}$ for a bend specimen; and<br>$\frac{0.75B\sigma_{\text{YSD}}(W - a_o)^2}{(2W + a_o)}$ for a compact specimen |
| $F_{\text{TS}}$   | maximum applied force observed after yield or plastic deformation in a dynamic tensile test, in kilonewtons                                                                                                                   |
| $J$               | experimental equivalent of the crack tip $J$ -integral, in megajoules per square metre                                                                                                                                        |
| $J_c$             | critical $J$ at the onset of brittle crack extension or pop-in when $\Delta a < 0.2$ mm, in megajoules per square metre                                                                                                       |
| $J_{\text{corr}}$ | critical $J$ where there is evidence of stable crack extension $\Delta a > 0.2$ mm, in megajoules per square metre                                                                                                            |

|             |                                                                                                                                                     |
|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| $J_m$       | critical $J$ at the first attainment of a maximum force plateau for fully plastic behaviour, in megajoules per square metre                         |
| $\dot{J}_p$ | rate of change of the plastic component of the $J$ -integral with time, in megajoules per square metre per second                                   |
| $J_u$       | critical $J$ at the onset of brittle crack extension or pop-in when the event is preceded by $\Delta a \geq 0.2$ mm, in megajoules per square metre |
| $K$         | stress intensity factor, in $\text{MPa} \cdot \text{m}^{0.5}$                                                                                       |
| $\dot{K}$   | rate of change of $K$ with time, in $\text{MPa} \cdot \text{m}^{0.5} \text{s}^{-1}$                                                                 |
| $K_{Ic}$    | plane strain fracture toughness, in $\text{MPa} \cdot \text{m}^{0.5}$                                                                               |
| $K_f$       | fatigue stress intensity factor applied during the final stages of fatigue crack extension, in $\text{MPa} \cdot \text{m}^{0.5}$                    |
| $K_Q$       | a provisional value of $K_{Ic}$ , in $\text{MPa} \cdot \text{m}^{0.5}$                                                                              |
| $L_c$       | parallel length of tensile specimen, in millimetres                                                                                                 |
| $L_e$       | extensometer gauge length of tensile specimen, in millimetres                                                                                       |
| $q$         | displacement of bend specimen or stepped notch compact specimen along the load-line, in millimetres                                                 |
| $\dot{q}$   | rate of change of $q$ with time, in millimetres per second                                                                                          |
| $q_c$       | value of $q$ at the onset of brittle crack extension or pop-in when $\Delta a < 0.2$ mm, in millimetres                                             |
| $q_e$       | elastic component of $q$ , in millimetres                                                                                                           |
| $q_m$       | value of $q$ at the first attainment of a maximum force plateau for fully plastic behaviour, in millimetres                                         |
| $q_p$       | plastic component of $q$ corresponding to $F_c$ , $F_u$ or $F_m$ , in millimetres                                                                   |
| $q_u$       | value of $q$ at the onset of brittle crack extension or pop-in when the event is preceded by $\Delta a \geq 0.2$ mm, in millimetres                 |
| $R$         | 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, in millimetres                                                                          |
| $S_o$       | original cross sectional area of tensile specimen, in square millimetres                                                                            |
| $SZW$       | stretch zone width, in millimetres                                                                                                                  |
| $t_a$       | time interval for linear part of force/time record, in seconds                                                                                      |
| $t_e$       | time interval for elastic deformation during fracture toughness determination, in seconds                                                           |
| $t_f$       | test specimen failure time interval, in seconds                                                                                                     |
| $t_p$       | time interval for plastic deformation of the test specimen, in seconds                                                                              |
| $t_r$       | rise time interval, in seconds                                                                                                                      |
| $T$         | test temperature, in degrees celsius                                                                                                                |
| $U$         | total area under plot of force $F$ versus load point displacement, in joules                                                                        |
| $U_e$       | elastic component of area under plot of force $F$ versus load point displacement, in joules                                                         |
| $U_p$       | plastic component of area under plot of force $F$ versus load point displacement, in joules                                                         |
| $G_t$       | total area under plot of force $F$ versus time, in kilonewton-seconds                                                                               |
| $V$         | notch opening displacement at or near to notch mouth ( $V = q$ in a stepped notch compact specimen), in millimetres                                 |
| $V_c$       | value of $V$ at the onset of brittle crack extension or pop-in when $\Delta a$ is less than 0.2 mm, in millimetres                                  |

|                        |                                                                                                                                                    |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| $V_e$                  | elastic crack mouth opening displacement at critical force, in millimetres                                                                         |
| $V_m$                  | value of $V$ at the first attainment of a maximum force plateau for fully plastic behaviour, in millimetres                                        |
| $V_p$                  | plastic component of $V$ corresponding to $F_c$ , $F_u$ or $F_m$ , in millimetres                                                                  |
| $V_u$                  | value of $V$ at the onset of brittle crack extension or pop-in when this is preceded by $\Delta a$ equal to or greater than 0.2 mm, in millimetres |
| $W$                    | effective width of test specimen, in millimetres                                                                                                   |
| $X, Y, Z$              | crack plane orientation symbols                                                                                                                    |
| $y$                    | half the distance between the knife edge fixing points, in millimetres                                                                             |
| $z$                    | distance of the notch opening gauge location above the surface of specimen, in millimetres                                                         |
| $\delta$               | crack tip opening displacement (CTOD)                                                                                                              |
| $\delta_c$             | critical CTOD at the onset of brittle crack extension or pop-in when $\Delta a < 0.2$ mm, in millimetres                                           |
| $\delta_{\text{corr}}$ | critical CTOD where there is evidence of stable crack extension $\Delta a > 0.2$ mm, in millimetres                                                |
| $\delta_m$             | critical CTOD at the first attainment of a maximum force plateau for fully plastic behaviour, in millimetres                                       |
| $\delta_p$             | plastic component of crack tip opening displacement, in millimetres                                                                                |
| $\dot{\delta}_p$       | rate of change in the plastic component of crack tip opening displacement with time, in millimetres per second                                     |
| $\delta_u$             | critical CTOD at the onset of brittle crack extension or pop-in when the event is preceded by $\Delta a \geq 0.2$ mm, in millimetres               |
| $\Delta a$             | average stable crack extension, including SZW (see 9.7.3), in millimetres                                                                          |
| $\Delta K$             | the difference between the maximum and minimum values of $K$ during any single cycle of fatigue precracking, in $\text{MPa} \cdot \text{m}^{0.5}$  |
| $\Delta p$             | load point displacement during plastic deformation of the test piece, in millimetres                                                               |
| $\dot{\epsilon}$       | strain rate to be applied during the determination of the dynamic 0.2 % proof strength (see Annex E), per second                                   |
| $\nu$                  | Poisson's ratio                                                                                                                                    |
| $\eta_p$               | plasticity factor used for $J$ -integral determination                                                                                             |
| $\sigma_{\text{TSP}}$  | tensile strength at the temperature of fatigue precracking, in MPa                                                                                 |
| $\sigma_{\text{YS}}$   | 0.2 % proof strength at the temperature of the fracture test <sup>2)</sup> , in MPa                                                                |
| $\sigma_{\text{YSD}}$  | 0.2 % proof strength at the temperature and loading rate of the fracture test, in MPa                                                              |
| $\sigma_{\text{YSP}}$  | 0.2 % proof strength at the temperature of fatigue precracking, in MPa                                                                             |
| $\sigma_{\text{USD}}$  | Tensile strength at the temperature and loading rate of the fracture test, in MPa                                                                  |

## 5 Principle

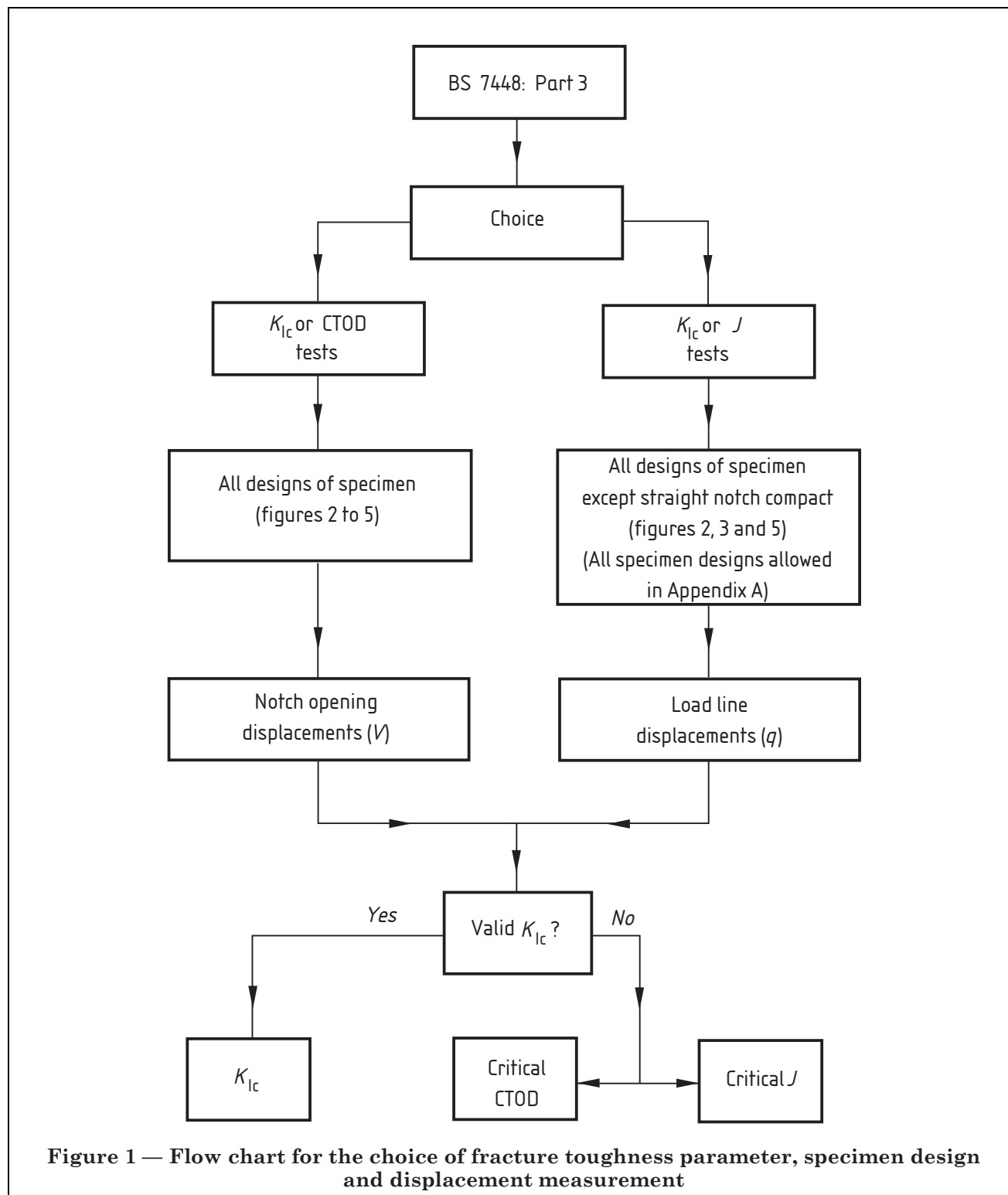
Fracture toughness tests are performed in two main stages. Firstly, a fatigue crack is produced in a notched specimen by applying an alternating force. Secondly, further crack extension is caused by applying an increasing displacement to the specimen. Specimens suitable for the displacement to be applied either by bending or by tension are specified.

During the second stage, force and displacement are measured with respect to time in order to provide the rates of application of force and displacement and also to enable a record of force versus displacement to be made.

NOTE A force/time record only is required for the method given in Annex A.

<sup>2)</sup> At present no British Standard exists for the measurement of tensile properties below ambient temperature or at high rates. However, in this standard, a satisfactory method of determining high rate tensile properties is given in Annex E, and guidance on performing low temperature tensile testing can be found in ISO 15579. In these cases the values to be used are subject to agreement between interested parties.

If negligible plastic deformation prior to crack extension is indicated then a plane strain fracture toughness value  $K_{Ic}$  is determined from the critical force. If the criteria for  $K_{Ic}$  are not met then elastic plastic fracture toughness values of crack tip opening displacement (CTOD) or  $J$  are determined from the critical displacement or deformation energy respectively, as indicated in Figure 1.



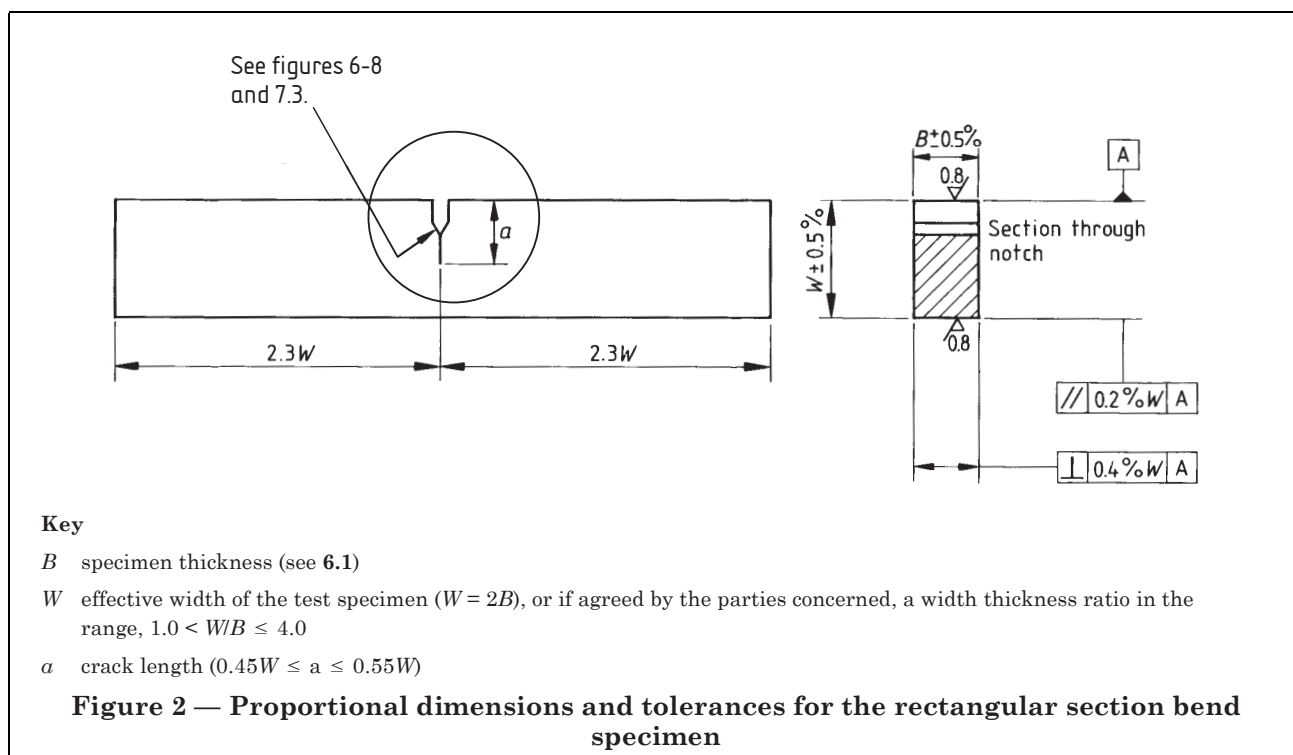
## 6 Test specimens

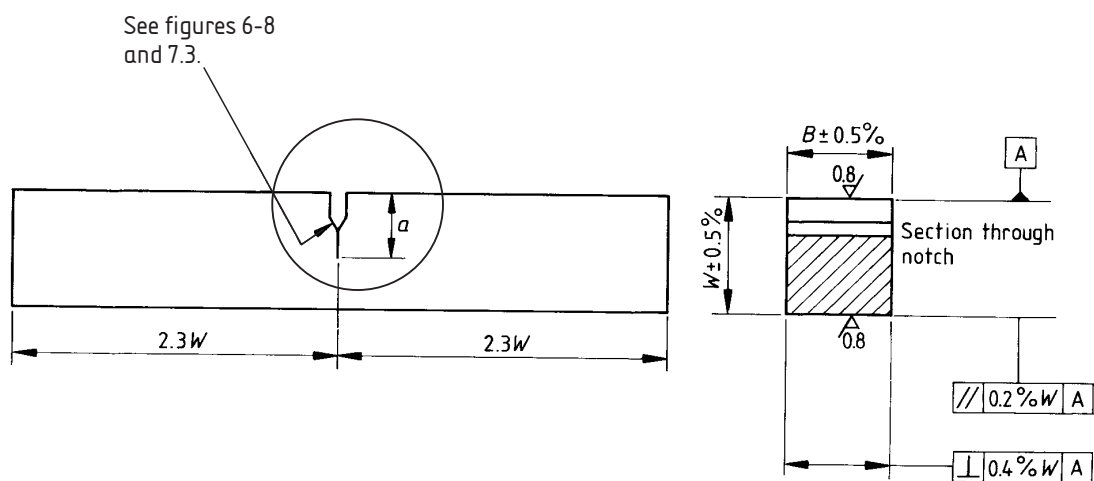
### 6.1 General

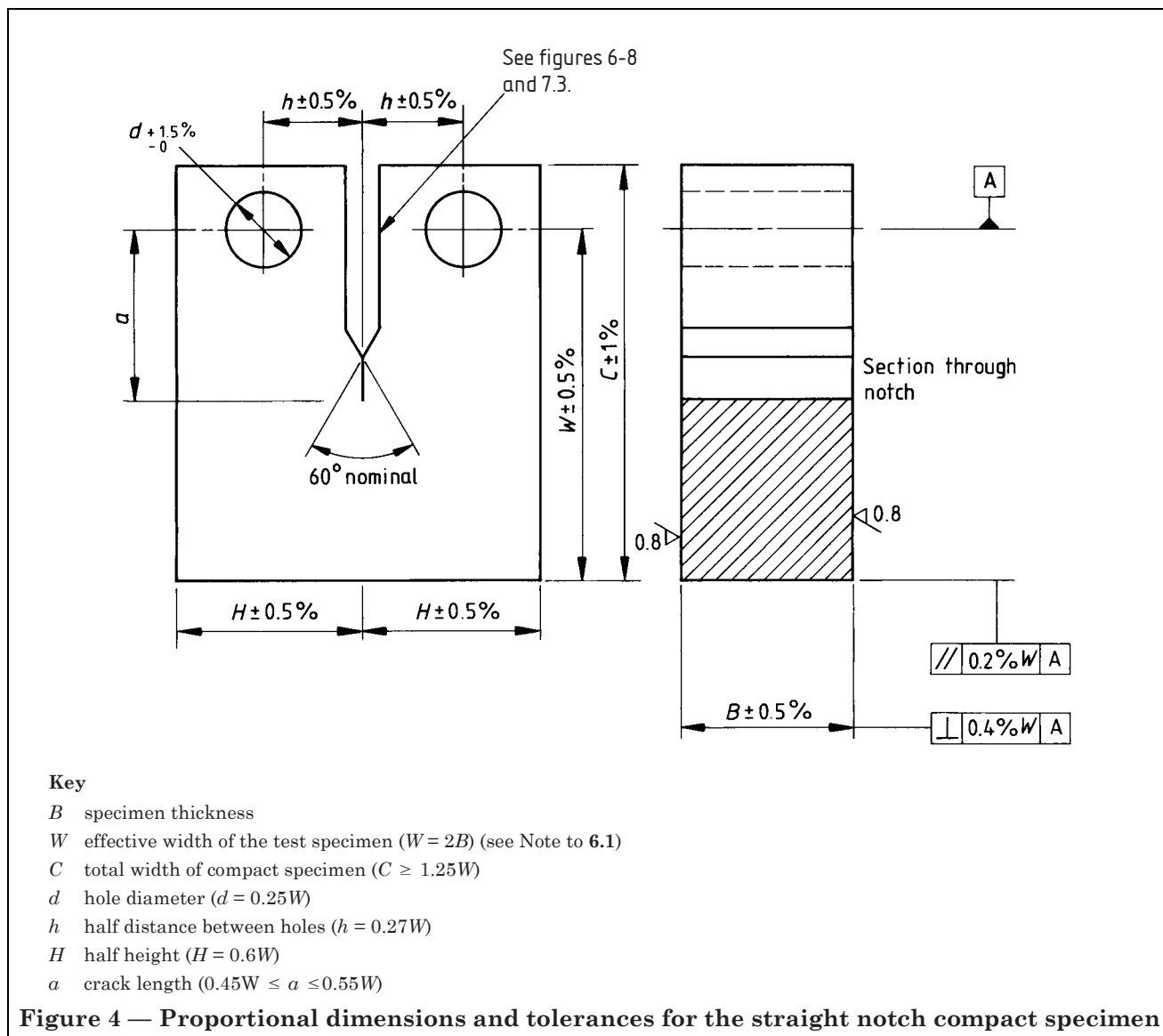
6.1.1 Each specimen shall be of one of the following designs (see 6.2):

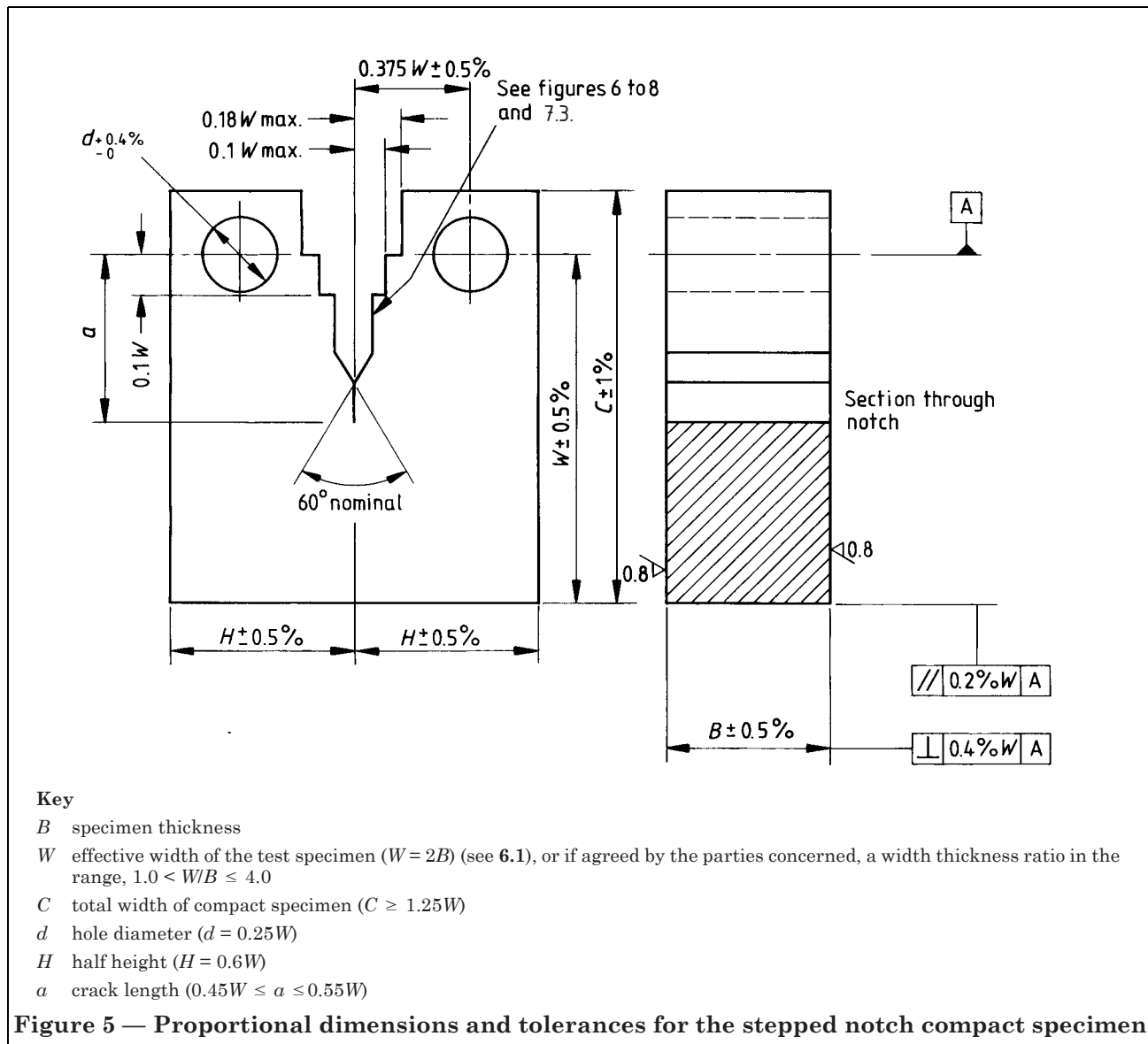
- rectangular cross-section three point bend (see Figure 2);
- square cross-section three point bend (see Figure 3);
- straight notch compact (see Figure 4);
- stepped notch compact (see Figure 5).

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



**Key** $B$  specimen thickness (see 6.1) $W$  effective width of the test specimen ( $W = B$ ) $a$  crack length ( $0.45W \leq a \leq 0.55W$ )**Figure 3 — Proportional dimensions and tolerances for the square section bend specimen**





**6.1.2** The test specimen shall have either the dimension  $B$  equal to the full thickness of the material to be tested, provided that they are reported (see Clause 12), test specimens having thicknesses less than the test material (sub-size and/or sidegrooved specimens) can 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 can apply when the specimen has adequate thickness to give a valid  $K_{Ic}$  value (see 6.3 and Table 1).

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

| $\frac{\sigma_{YSD}}{E}$ |                     | Crack length $a$ , or thickness $B$ or ligament $W - a$ |
|--------------------------|---------------------|---------------------------------------------------------|
| Over                     | Up to and including | mm                                                      |
| —                        | 0.0050              | 100                                                     |
| 0.0050                   | 0.0057              | 75                                                      |
| 0.0057                   | 0.0062              | 63                                                      |
| 0.0062                   | 0.0065              | 50                                                      |
| 0.0065                   | 0.0071              | 38                                                      |
| 0.0071                   | 0.0080              | 25                                                      |
| 0.0080                   | 0.0095              | 13                                                      |
| 0.0095                   | —                   | 6.5                                                     |

b) when there is an established correlation between full specimen thickness and sub-size specimens tested;

c) when no value of thickness is given in a product specification; in this case the specimen dimension  $B$  shall be as thick as possible;

NOTE 2 Sub-size and/or sidegrooved specimens might give values of fracture toughness different to those associated with full thickness specimens.

d) when sidegrooved specimens are used, an effective specimen thickness of  $\sqrt{BB_N}$  shall be used in the calculation of  $K$  and the elastic components of CTOD and  $J$ ; the net section thickness  $B_N$  shall be used in the calculation of the plastic component of  $J$ .

**6.1.3** The notch profile shall be such that it is within the envelope shown in Figure 6a).

One of the following notch configurations shall be used:

a) When a milled notch is used, in order to expedite fatigue precracking, the notch root radius shall be not greater than 0.10 mm.

b) 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.

c) If fatigue crack initiation and/or propagation are difficult to control (see 7.4.6), 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  $\pm 2^\circ$ . When required, knife edges shall be machined into the specimen or attached and 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  $0.5^\circ$ . 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 3 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 6.2.1).

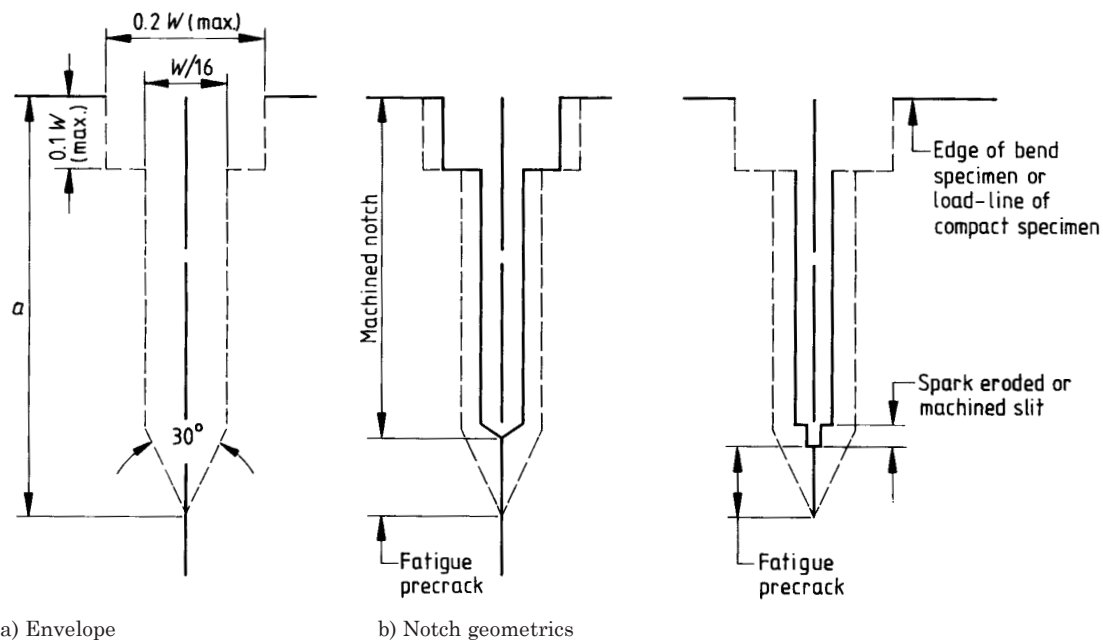
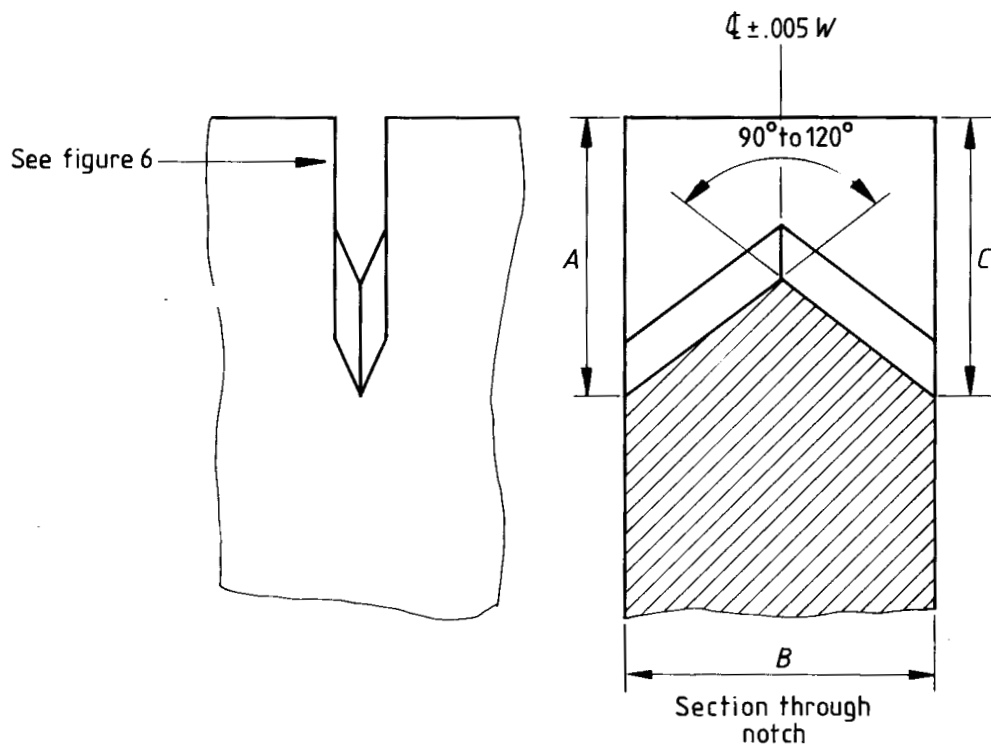


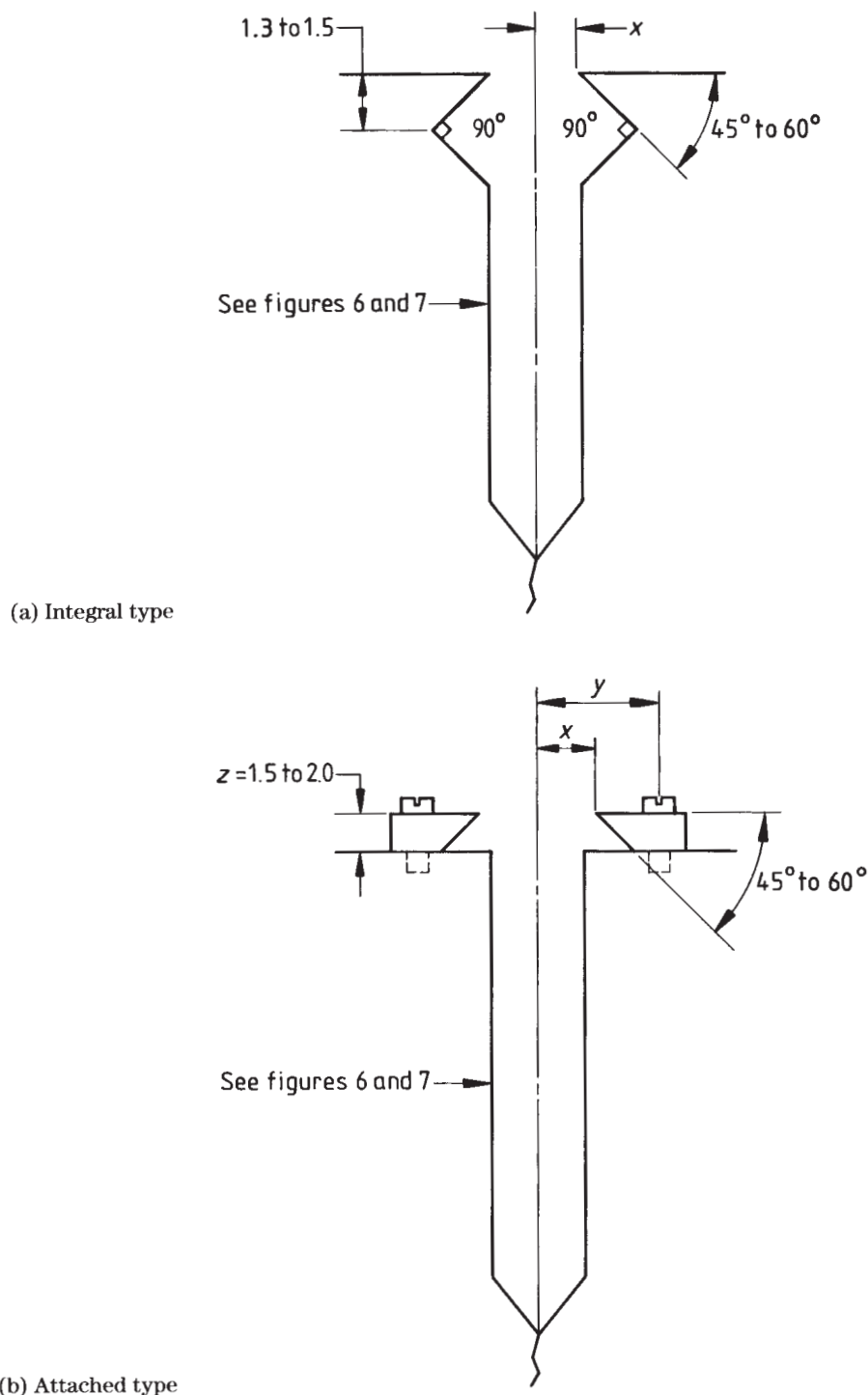
Figure 6 — Acceptable fatigue crack starter notches and fatigue crack configurations



NOTE 1  $A_1 = A_2$ , within  $0.010W$ .

NOTE 2 Cutter tip angle  $90^\circ$  max.

Figure 7 — Chevron notch



$$2x \leq W/2$$

$$2y + \text{screw thread diameter} \leq W/2$$

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

**Figure 8 — Outward pointing knife edges and corresponding notch geometrics**