British Standard

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08 March 2004

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BRITISH STANDARD

BS 7448 : Part 2 : 1997

Fracture mechanics toughness tests

Part 2. Method for determination of K_{Ic}, critical CTOD and critical J values of welds in metallic materials

ICS 25.160.40

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee ISE/NFE/4, Mechanical testing of metals, upon which the following bodies were represented:

British Iron and Steel Producers Association
British Non-ferrous Metals Federation
British Railways Board
Copper Development Association
Electricity Association
ERA Technology Ltd.
GAMBICA (BEAMA Ltd.)
Institute of Materials
Ministry of Defence
National Physical Laboratory
Society of British Aerospace Companies Limited
United Kingdom Accreditation Service
University College London
Welding Institute

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

BEAMA Ltd.
Castings Development Centre
Lloyds Register of Shipping

This British Standard, having been prepared under the direction of the Engineering Sector Board, was published under the authority of the Standards Board and comes into effect on 15 August 1997

Amendments issued since publication

Amd. No.	Date	Text affected

The following BSI references relate to the work on this standard:
Committee reference ISE/NFE/4
Draft for comment 96/706339 DC

ISBN 0 580 27997 9

Contents

Foreword

This Part of BS 7448 has been prepared by Technical Committee ISE/NFE/4.

It gives a method for determining the fracture mechanics toughness of welded joints in metallic materials under displacement controlled monotonic loading.

This Part of BS 7448 extends the following Parts of this standard to cover welded joints:

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

Part 4. *Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials.*

NOTE. Part 4 is in preparation and will be published soon.

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

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.

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 and ii, pages 1 to 28, an inside back cover and a back cover.

1 Scope

This Part of BS 7448 specifies the specimen design, preparation, method for notch placement and post test validation of the notch placement applicable to specimens prepared from welds (i.e. specimens testing the weld metal or heat affected zone).

This method is complementary to BS 7448 : Parts 1 and 4, which cover all aspects of the fracture toughness test and which need to be used in conjunction with this document. The method uses fatigue precracked specimens which have been notched after welding, into a specified target area in the weld. The target area and notch orientation to be used is specified by the customer. The specimens are tested in displacement control under quasi-static loading and at a constant rate of increase in stress intensity factor within the range 0.5 $MPa{\cdot}m^{0.5}\,s^{-1}$ to 3.0 $MPa{\cdot}m^{0.5}\,s^{-1}$ during the initial elastic deformation. Methods are described to evaluate the suitability of a weld for notch placement within the target area which is either within the weld metal or the heat affected zone (HAZ) and then, where appropriate, to evaluate the effectiveness of the fatigue crack in sampling these areas.

2 References

2.1 Normative references

This Part of BS 7448 incorporates, by dated or undated reference, provisions from other publications. These normative references are made at the appropriate places in the text and the cited publications are listed on the inside back cover. For dated references, only the edition cited applies; any subsequent amendments to or revisions of the cited publication apply to this Part of BS 7448 only when incorporated in the reference by amendment or revision. For undated references, the latest edition of the cited publication applies, together with any amendments.

2.2 Informative references

This Part of BS 7448 refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

3 Definitions

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

3.1 stress intensity factor (K)

The magnitude of the elastic stress field singularity for a homogeneous, linear-elastic body.

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

3.2 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.

3.3 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.

3.4 crack tip opening displacement (CTOD)

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

3.5 critical CTOD

A value of CTOD associated with a particular type of crack extension (see clause **4**).

3.6 J-integral

A line or surface integral that encloses the crack front from one crack surface to the other, which characterizes the local stress-strain field at the crack tip, expressed in MJ/m^2 [1)].

3.7 J

An experimental equivalent of the J-integral determined by the method given in the present standard.

3.8 critical J

A value of J associated with a particular type of crack extension (see clause **4**).

3.9 brittle crack extension

An abrupt crack extension which occurs with or without prior stable crack extension.

3.10 stable crack extension

Crack extension which, in displacement control, stops when applied displacement is held constant.

3.11 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 **3.13**) or slow stable crack extension, and which occurs in the same plane as the fatigue precrack.

3.12 target area

The intended fatigue crack tip position within the weld.

[1)] 1 MJ/m^2 = 1 MN/m.

3.13 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.

3.14 local compression

Controlled compression applied to specimens in the thickness direction on the unnotched ligament by means of hardened steel platens prior to fatigue cracking, (see annex D).

3.15 welding

An operation in which two or more parts are united, by means of heat or pressure or both, in such a way that there is continuity in the nature of the metal between these parts. A filler metal, the melting temperature of which is of the same order as that of the parent metal, may or may not be used[2)].

3.16 weld

A union of pieces of metal made by welding.

3.17 weld metal

All metal melted during the making of a weld and retained in the weld.

3.18 parent metal

Metal to be joined by welding.

3.19 heat-affected zone (HAZ)

The zone of the parent metal that is metallurgically affected by the heat of welding.

3.20 fusion line (f)

The junction between the weld metal and the heat affected zone.

3.21 weld positional (WP)

Target position for the fatigue crack tip defined with respect to a reference line (for examples, see figure A.1).

3.22 specific microstructure (SM)

Target microstructure for the fatigue crack tip (for examples, see figure A.2).

3.23 weld width (2*h*)

Shortest distance between adjacent fusion lines of the weld at the fatigue crack tip position measured perpendicular to the crack plane, (see figure 11).

3.24 specimen blanks

Specimen prepared from weld prior to notching.

3.25 post-weld heat treatment

Heat treatment applied after welding for the purpose of reducing residual stresses or modifying weld properties.

4 Symbols and designations

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

a	nominal crack length, in millimetres
a_o	weighted average original crack length, in millimetres (see BS 7448 : Part 1)
B	specimen thickness, in millimetres
B_N	net specimen thickness after sidegrooving, in millimetres
d_1, d_2	lengths of microstructural features associated with pop-in, in micrometres
F	applied force, in kilonewtons
F_f	maximum fatigue precracking force during the final stages of fatigue crack extension, in kilonewtons
GCHAZ	grain coarsened HAZ
HV	Vickers hardness values
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 plastic 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_f	maximum fatigue stress intensity factor applied during the final stages of fatigue precrack
N	normal to welding direction
P	parallel to welding direction
Q	weld thickness direction
$R_{p0.2}$	0.2 % proof strength at the temperature of the fracture test, in newtons per square millimetre or megapascals
$R_{p0.2b}$	0.2 % proof strength for the base material at the temperature of the fracture test, in newtons per square millimetre or megapascals
$R_{p0.2w}$	0.2 % proof strength for the weld metal at the temperature of the fracture test, in newtons per square millimetre or megapascals
R_m	tensile strength at the temperature of the fracture test, in newtons per square millimetre or megapascals
R_{mb}	tensile strength of the base material at the temperature of the fracture test, in newtons per square millimetre or megapascals
R_{mw}	tensile strength of the weld metal at the temperature of the fracture test, in newtons per square millimetre or megapascals
s	distance between crack tip and target area measured in the crack plane, in millimetres
S	span between the two outer points in a three point bend test, in millimetres

[2)] See BS 499 : Part 1 : 1991.

T	fracture toughness test temperature, in degrees centigrade
W	specimen width, in millimetres
X	direction parallel to primary grain flow of parent metal
Y	direction transverse to primary grain flow of parent metal
Z	direction through the thickness of parent metal
δ_c	critical CTOD at the onset of brittle crack extension or pop-in when Δa is less than 0.2 mm, in millimetres
δ_m	value of CTOD at the first attainment of a maximum force plateau for fully plastic behaviour, in millimetres
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, in millimetres
Δa	stable crack extension, including SZW, in millimetres
Δa_{pop}	maximum length of brittle crack extension associated with pop-in, in millimetres
λ	length of specific microstructure measured in pre- or post-test metallography, in micrometres

5 Principle

This standard prescribes procedures for the measurement of fracture toughness on notched specimens taken from welds. It addresses two situations: (i) where the notch is located in relation to specific weld features i.e. weld positional (WP), and (ii) where a target microstructure at the final crack tip location is defined, i.e. specific microstructure (SM). This may include metallographic examination of the weld to confirm that the target microstructure is present and in sufficient quantity for testing.

The specimen geometry and notch orientation is then chosen and a fatigue crack is extended into the target microstructure by applying an alternating force within controlled limits. Modifications to the fatigue precracking conditions may be necessary to grow a straight fronted crack and to minimize the effects that welding residual stresses may have on the result in as-welded or partially stress relieved welds.

The fracture toughness test is performed and evaluated as described in BS 7448 : Part 1 or Part 4, but subject to additional requirements of this standard on the calculation of fracture toughness (see **12.3**) and crack front straightness (see **12.4**).

Post-test metallography may be required to establish whether the final crack tip was located in the target microstructure and to determine the significance of pop-ins.

The methods used in this procedure are summarized in figure 1.

6 Choice of specimen design, orientation and notch location

6.1 Classification of target area for notching

Specimens selected for WP testing shall be specified to test a defined weld region with respect to a reference position (e.g. weld metal centreline).

Specimens selected for SM testing shall sample the specified microstructure along the whole or part of the crack front length within the central 75 % of specimen thickness.

NOTE. Some examples of WP and SM notch locations are given in annex A.

6.2 Specimen design

The specimen design shall be of compact (CT) or single edge notch bend (SENB) geometry as defined in **5.1** of BS 7448 : Part 1: 1991 or in **6.1** of BS 7448 : Part 4 : 1997 and shall be plain sided or sidegrooved.

NOTE 1. The tolerances on specimen dimensions are more relaxed than when testing plain metallic materials, see **8.1**.

The test specimen shall have the dimension B equal to the full thickness of parent material adjacent to the weld to be tested (i.e. excluding the thickness of the weld overfill).

B shall be measured in the direction Q shown in figure 2.

NOTE 2. Testing of sub-size (i.e. $B <$ thickness in direction Q in figure 2) and/or sidegrooved specimens is permitted, provided that this is reported and justified for the same circumstances that are given in **5.1.2** of BS 7448 : Part 1 : 1991. Testing of sub-sized and/or sidegrooved specimens may give values of fracture toughness different from full thickness specimens owing to size effects and/or because different microstructural regions have been tested.

6.3 Specimen and crack plane orientation

The specimen and crack plane orientation relative to the weld direction shall be defined using the identification system described in figure 2.

7 Pre-machining metallography

7.1 Microstructural assessment of macrosections

When the notch target area is defined as SM, macro-sections shall be prepared with the plane of the section perpendicular to the welding direction. At least two macrosections shall be prepared from positions bounding the length of weld to be tested to ensure that the target microstructure is present at the expected crack tip position and suitable for testing. The macrosections shall be polished and etched for metallography and examined at a magnification suitable to identify the target area prior to making the fracture toughness specimens.

The positions of macrosections shall be recorded.

The examination of the macrosections shall be used to establish whether the crack tip in a through-thickness notched specimen is likely to be located in the target area which is within the central 75 % of thickness. When a surface notched specimen is used, the target area shall be ahead of the final crack tip by no more than 0.5 mm.

If the specified microstructure is not present, or there is insufficient quantity to test reliably, or the crack tip position tolerances cannot be achieved, the weld shall be rejected as unsuitable for testing to the SM criteria. (If the weld is rejected, the target area criteria can be modified, or a new weld prepared).

7.2 Additional requirements for heat affected zone tests

When the target area is SM in the visibly transformed HAZ, the following microstructure examinations, additional to those of **7.1** shall be conducted on the polished and etched macrosection.

The examination shall be conducted along the likely crack tip position to assess whether the target microstructure is within the central 75 % of thickness and in sufficient quantity for a successful test.

The measured positions and lengths of the target microstructure shall be presented in map form (an example is shown in annex B). The map shall be drawn to include the full macrosection thickness, showing the positions of the target microstructure. The percentage of the target microstructure shall be calculated over the middle 75 % of the specimen plate thickness.

Where surface notched specimens are specified, the macrosection shall be examined to confirm that the target microstructure is present within the ratios of a_0/W defined in **6.4.7** of BS 7448 : Part 1 : 1991 or **7.4.6** of BS 7448 : Part 4 : 1997, as appropriate.

The suitability of the weld for the location of the fatigue crack tip within the target area shall be assessed. If a successful placement of the fatigue crack tip with respect to the SM acceptance criteria is not likely, then consideration shall be given to revising the definition of the target area or preparing a new weld.

8 Machining

8.1 Tolerances on specimen dimensions

Prior to notching, specimen blanks shall be prepared.

NOTE 1. To facilitate testing of the original product using single edge notch bend specimens, the shape and surface finish, the tolerances on specimen dimensions, squareness and straightness are more relaxed than in **5.1** of BS 7448 : Part 1 : 1991.

Compact specimens shall be fully machined to meet the geometry and tolerances on specimen shape defined in **5.1.1** of BS 7448 : Part 1 : 1991 and **6.1.1** of BS 7448 : Part 4 : 1997. The tolerances for rectangular and square section bend specimens are defined in figure 3. Tolerances for weld misalignment, distortion, and specimen blank curvature (when removing specimen blanks from pipe sections) shall be as defined in figure 4.

NOTE 2. The required straightness tolerance of 2.5 % W on the specimen blank sides will allow for pipe curvature for ratios of pipe radius to weld thickness ≥ 10.

When full section thickness specimen blanks are used, machining shall be kept to a minimum in order to conform to the tolerance requirements and the requirements for local compression (see note 2 to **9.1**). The weld overfill shall be machined flush with the original product surface.

When the material thicknesses either side of the weld differ by 10 % or more, the blank shall be machined down to the thickness of the thinner material. In such cases the original and final specimen blank dimensions shall be reported.

Welded joints not meeting the straightness/misalignment requirements identified above shall be straightened prior to notching by local bending. The load bearing points and plastic deformation shall be located at a distance ≥ B from the region to be notched.

NOTE 3. A method for straightening specimen blanks from distorted or curved sections is illustrated in figure 5.

For intended crack plane orientations NP and NQ (see figure 2), the crack plane shall be parallel to the weld direction P.

8.2 Notch placement for through-thickness notched specimens

When through-thickness notching is specified, the surface of the specimen blank to be notched, and the opposite surface, shall be ground and etched to reveal the weld and HAZ. After identifying the target area, a line shall be scribed onto the surface to mark the position for the machined notch.

The scribed line shall be made on both prepared surfaces in a manner which best represents the notch line on the pre-test macrosections. The lines (on each of the prepared surfaces) extended down the perpendicular surfaces of the specimen blank shall be averaged and, if necessary, a new line drawn on the specimen blank to indicate the position for the machined notch (see figure 6), which is most likely to result in the crack tip being located in the target area.

To ensure that the final crack tip tests the target area, the angle between the scribed line on the surface to be notched and specimen blank axis shall be 90° ± 5° (maximum), see figure 6.

8.3 Notch placement for surface notched specimens

When surface notching is specified, the surfaces of the specimen blank at right angles to the surface to be notched shall be ground and etched to reveal the weld metal and HAZ. The target area on each of the prepared surfaces shall be identified and lines scribed from the target area to the surface to be notched. Any lateral displacement of the two lines shall be averaged and, if necessary, a new line drawn on the surface to be notched to indicate the position for the machined notch (see figure 7).

To ensure that the final crack tip tests the target area, the angle between the scribed line on the surface to be notched and the specimen blank axis shall be $90^\circ \pm 5^\circ$ (maximum), see figure 7.

8.4 Machine notching

The machine notching procedure and requirements shall be as described in **5.1.3** and **6.3** of BS 7448 : Part 1 : 1991.

9 Specimen preparation

9.1 Fatigue precracking

The general fatigue precracking requirements shall be the same as those specified in **6.4** of BS 7448 : Part 1 : 1991, but with the following exceptions. For weld metal tests, the calculation of the maximum fatigue precracking force, F_f, and maximum fatigue stress intensity factor, K_f, shall be based on the tensile properties of the weld metal, i.e. the region in which the fatigue crack will be located. In all other cases the properties of the adjacent material which has the lowest tensile properties shall be used.

Any post-weld or stress relief heat treatment shall be completed before commencing fatigue precracking.

NOTE 1. When possible, the use of the shortest fatigue crack length permitted in **6.4.7** of BS 7448 : Part 1 : 1991 is recommended. This minimizes fatigue crack front bowing and problems of the crack deviating from the specified target area.

Problems can occur in meeting the fatigue crack front straightness requirements of **12.4** particularly with specimens prepared from as-welded or partially stress relieved welds. In these instances the procedures given in annex D shall be considered.

NOTE 2. The magnitude and distribution of residual stresses in as-welded and partially stress relieved specimens depend on the material, welding procedure, the degree of restraint, and the post-weld specimen preparation.

NOTE 3. Residual stresses may (or may not) contribute to uneven fatigue crack extension, but they will have an effect on the resulting fracture toughness values determined from the test specimens.

NOTE 4. Clause **12.5** provides a description of the parameters used to identify fracture toughness obtained from specimens taken from welds.

If the specimen is prepared from a stress relieved weld, or if the specimen is shown to contain low residual stresses (see **D.5**), then the procedures in **D.1** to **D.4** may not be necessary. The fracture toughness determined from the test shall be identified as specified in **12.5**a.

If the residual stresses cannot be shown to be low, but the fatigue precrack meets the straightness requirements of **12.4**, the fracture toughness determined from the test shall be identified as specified in **12.5**b.

NOTE 5. A straight fatigue crack front may be due to the crack tip sampling:

a) low residual stresses; or

b) a uniform level of tensile or compressive residual stresses.

If the fatigue precrack does not meet the straightness requirements of **12.4**, then modifications to the fatigue-precracking procedure shall be made in accordance with annex D. If the specimen then meets the crack front straightness requirements of **12.4** and the residual stresses are shown to be low in accordance with **D.5**, the fracture toughness value shall be identified as required in **12.5**c. When the requirements of **D.5** cannot be met, the results shall be identified as specified in **12.5**d.

9.2 Sidegrooving

Where sidegrooving is specified, this shall be conducted in accordance with the requirements of **6.2** of BS 7448 : Part 4 : 1997.

10 Test procedure for K_{Ic}, CTOD (or δ) and J tests

The procedure for K_{Ic}, CTOD (or δ) and J testing shall be as described in clause **8** of BS 7448 : Part 1 : 1991 or clause **9** or clause **10** of BS 7448 : Part 4 : 1997, as appropriate.

11 Post-test metallography

11.1 General

Post-test metallography shall be applied to specimens designated for SM testing in order to establish if the crack tip has been successfully located in the target microstructure. A slice containing the fracture face shall be cut from the specimen. When the target area is the HAZ, the slice shall be removed from the side of the specimen containing the weld metal. This slice shall be used for the post-test sectioning analysis described in **11.2** and **11.3** to establish the microstructure at the fatigue crack tip.

Post-test sectioning is not required on tests in which the target area is WP to meet the requirements of this standard.

NOTE. In the case of brittle fracture, confirmation that the crack tip sampled the specified microstructure does not guarantee that cleavage initiation occurred in that microstructure. Further sectioning and metallography may be necessary (when requested by the customer) to identify the microstructure at fracture initiation. The sectioning procedures are the same as described for the assessment of pop-in, and are given in annex E.

11.2 Through-thickness notched specimens

11.2.1 *Sectioning*

The slice of the fracture surface from a through-thickness notched specimen shall be sectioned on a plane perpendicular to the fracture surface and original parent material surface immediately behind the fatigue crack tip (see figure 8, slice A). This shall be at a position within 2 mm of maximum crack depth and shall include the fatigue crack over the central 75 % of specimen thickness (B, or B_N in the case of sidegrooved specimens). The cut surface of the sectioned slice nearest the machine notch (slice A in figure 8) shall be prepared for metallography to establish whether the fatigue crack successfully sampled the specified microstructure.

11.2.2 ***Assessment***

The prepared metallographic section shall be examined, at a suitable magnification using optical microscopy, to establish if the fatigue crack tip front sampled the SM and to confirm that this was located within the central 75 % of specimen thickness (B or B_N). A microstructural map shall be prepared which records the positions and lengths of the specified microstructure within the central 75 % of specimen thickness (B or B_N). An example for a specimen notched into the transformed HAZ is shown in annex C.

Sections taken at the brittle fracture initiation position (when requested by the customer) shall be examined and the initiation microstructure recorded. Sectioning procedures are the same as described for the assessment of pop-in and are given in annex E.

11.3 Surface notched specimens

11.3.1 ***Sectioning***

At least one section shall be taken within the middle 75 % of specimen thickness (B or B_N). The plane of the section shall be perpendicular to the notched surface and the crack plane (see figure 9).

11.3.2 ***Assessment***

The prepared metallographic section shall be examined at suitable magnification under an optical microscope to establish if the fatigue crack tip sampled the specified microstructure. If the specified microstructure is ahead of the fatigue crack tip, the minimum separation distance, s, shall be measured, with an accuracy of $\pm$ 0.05 mm, (see figure 10). (It may be necessary to section both fracture surfaces to establish this distance).

11.4 Assessment of pop-in

The weld shall be assessed for pop-in as described in annex E.

Pop-ins giving both force drops and displacement increases of less than 1 % shall be ignored. All other pop-ins shall be considered significant unless shown to be insignificant by the fractographic and metallographic procedures described in annex E.

NOTE. The criteria for the assessment of pop-in described in BS 7448 : Part 1 are intended for testing homogeneous material, and may be inappropriate when applied to welds. Experience indicates that with weld testing, the size of the pop-in may be related to the length of brittle material present at the crack tip. Small changes in crack tip position can alter the size of the pop-in.

12 Post-test analysis

12.1 Choice of tensile properties

The tensile properties of the region in which the crack tip lies are required, at the fracture toughness test temperature, for the calculation of fracture toughness and qualification assessment. When the crack tip is located completely in the weld metal, the tensile properties shall be those measured using an all-weld metal specimen. For a crack tip located in, or partially in, the transformed HAZ, the higher of the parent material or weld metal strengths shall be used.

For carbon and carbon manganese steels, where tensile properties of the weld metal and parent material cannot be measured directly, estimates from correlations with hardness tests may be used. The following correlations are appropriate for estimating room temperature yield strength in N/mm^2 or MPa:

Parent material, $R_{p0.2b} = 3.28\text{HV} - 221$, for $160 < \text{HV} < 495$

where HV is the measured diamond pyramid number.

Weld metal, $R_{p0.2w} = 3.15\text{HV} - 168$, for $150 < \text{HV} < 300$

Parent material and weld metal room temperature tensile strength can be estimated from:

R_{mb} or $R_{mw} = 3.3\text{HV} - 8$, for $100 < \text{HV} < 250$

and,

R_{mb} or $R_{mw} = 3.15\text{HV} + 93$, for $250 < \text{HV} < 400$

Yield strength (in N/mm^2) obtained for ferritic steels at room temperature may be estimated for lower temperatures from the following equations:

$$R_{p0.2} = R_{p0.2} \text{ (at room temperature)} + \frac{10^5}{(491 + 1.8T)} - 189$$

where T is the temperature in °C in the fracture toughness test.

12.2 K_{Ic}

Interpretation of the test record to determine K_{Ic} shall be in accordance with **9.2** of BS 7448 : Part 1 : 1991, but with the additional requirements of **12.1** of this Part of BS 7448.

12.3 CTOD (or δ) and J

Interpretation of the test record to determine CTOD (or δ) and J shall be in accordance with **9.3.2** and **9.4** of BS 7448 : Part 1 : 1991 or **11.2** and **11.3** of BS 7448 : Part 4 : 1997, as appropriate, but subject to the additional requirements in **12.1**.

For specimens testing weld metal, the CTOD (or δ) estimation procedures for the initiation of fracture in BS 7448 : Part 1 and Part 4 shall be considered to be qualified for the purposes of the present standard when the following conditions are met.

a) For cases where the crack is in the centre of the weld: the ratio of weld width (over the central 75 % of thickness) to the ligament length is greater than 0.2, i.e. $2h/(W - a_o) > 0.2$ (see figure 11a and b).

b) For cases where the crack is offset from the weld centre line: the ratio of the shortest distance between the crack plane and the weld fusion boundary (over the central 75 % of thickness) to the ligament length is greater than 0.1, i.e. $2h/(W - a_o) > 0.1$ (see figure 11c and d).

c) For both cases a) and b) above, an additional requirement is that the ratio of weld metal yield strength to parent metal yield strength shall be in the range 0.50 to 1.50 when determining CTOD (or δ), i.e:

$$0.50 < \frac{R_{p0.2w}}{R_{p0.2b}} < 1.50$$

For specimens testing weld metal, the J estimation procedures for the initiation of fracture in BS 7448 : Part 1 and Part 4 shall be considered qualified for the purposes of the present standard when the ratio of weld metal yield strength to parent metal yield strength is in the range 0.50 to 1.25, i.e:

$$0.50 < \frac{R_{p0.2w}}{R_{p0.2b}} < 1.25$$

For specimens testing the HAZ, the CTOD (or δ) and J estimation procedures in BS 7448 : Part 1 and Part 4 shall be used (see **12.1** for choice of yield strength when calculating CTOD). When reporting results the yield strengths of the parent material and weld metal shall be stated.

NOTE 1. The estimation procedures will result in less than ± 10 % error in CTOD or J. Overestimates of CTOD occur if $R_{p0.2w}/R_{p0.2b}$ > 1.50, or 1.25 for J; underestimates occur if $R_{p0.2w}/R_{p0.2b}$ < 0.50 for CTOD and J.

NOTE 2. The CTOD and J equations in BS 7448 : Part 4 may be in error when applied to R-curve estimation on welds with weld metal yield strength mismatch when CTOD and J values exceed δ_m or J_m , respectively.

12.4 Qualification requirements

12.4.1 *General*

All the qualification checks listed in clause **10** of BS 7448 : Part 1 : 1991 shall be applicable but with the following modifications.

Where CTOD and J are assessed using bend specimens, the fatigue crack front straightness requirements in **8.7.2**b and **10.2.3**c of BS 7448 : Part 1 : 1991 shall be increased from 10 % to 20 % (viz. no two of the inner seven crack length measurements shall differ by more than 20 % a_o). The fatigue crack straightness requirements for compact specimens and K_{Ic} tests (both compact and bend specimens) shall be the same as specified in **8.7.2**b and **10.2.3**c of BS 7448 : Part 1 : 1991.

NOTE. In order to achieve the requirements of SM and WP testing, it may not be possible to allow a relaxation to the fatigue crack front straightness requirements, and the more stringent requirements of BS 7448 : Part 1 : 1991 may be necessary.

12.4.2 *Through-thickness notched specimens*

Where post-test sectioning and metallography conducted on SM specimens in accordance with **11.2** shows that the fatigue crack front sampled the designated target area and, where specified, the designated lengths of specified microstructure, within the central 75 % of specimen thickness (B or B_N), the fracture toughness result shall be considered qualified. When these requirements are not achieved, the fracture toughness of the specified microstructure has not been measured and the test result shall be considered not qualified.

12.4.3 *Surface notched specimens*

Where post-test sectioning and metallography conducted on SM specimens in accordance with **11.3** shows that the fatigue crack tip has sampled the specified microstructure, or the dimension s (see **11.3.2**) is < 0.5 mm, the fracture toughness result shall be considered qualified. When these requirements are not achieved, the fracture toughness of the specified microstructure has not been measured and the test result shall be considered not qualified.

12.5 Symbols used to identify fracture toughness values from welds

The following symbols shall be used to identify the fracture toughness of welds. These shall be in addition to those required in **12.2** and **12.3**.

a) K, J and δ (with no superscripts) shall be used when the weld is stress relieved or in as-welded or partially stress relieved specimens where it can be demonstrated that low residual stresses are present (see **D.5**).

b) K^*, J^* and δ^* (asterisk as superscript) shall be used to identify specimens from as-welded or partially stress relieved specimens where no modified precracking procedure (in accordance with annex D) has been used.

c) K^M, J^M and δ^M (M as superscript) shall be used to identify results for specimens when a modified precracking procedure in accordance with annex D has been used to provide a straight crack front and the residual stresses have been shown to be low (see **D.5**).

d) K^{M*}, J^{M*} and δ^{M*} (M as superscript followed by an asterisk) shall be used to identify results for specimens when a modified precracking procedure in accordance with annex D has been used but the requirements of **D.5** are not achieved.

13 Test report

The test report shall be in accordance with clause **11** of BS 7448 : Part 1 : 1991 with the following additions:

a) record of weld positional (WP) or specified microstructure (SM) notching;

b) specimen geometry and dimensions;

c) crack plane orientation in accordance with figure 2;

d) original thicknesses of the weld and parent material adjacent to the weld;

e) pre-test metallography results on macrosection examination (if appropriate);

f) tensile properties of the weld and parent material and method used to derive the values;

g) weld width, 2h or h, as appropriate;

h) method used to achieve a straight fatigue crack front, if appropriate;

i) assessment of pop-in significance (if appropriate);

j) qualification of result with respect to the crack sampling the designated target area.

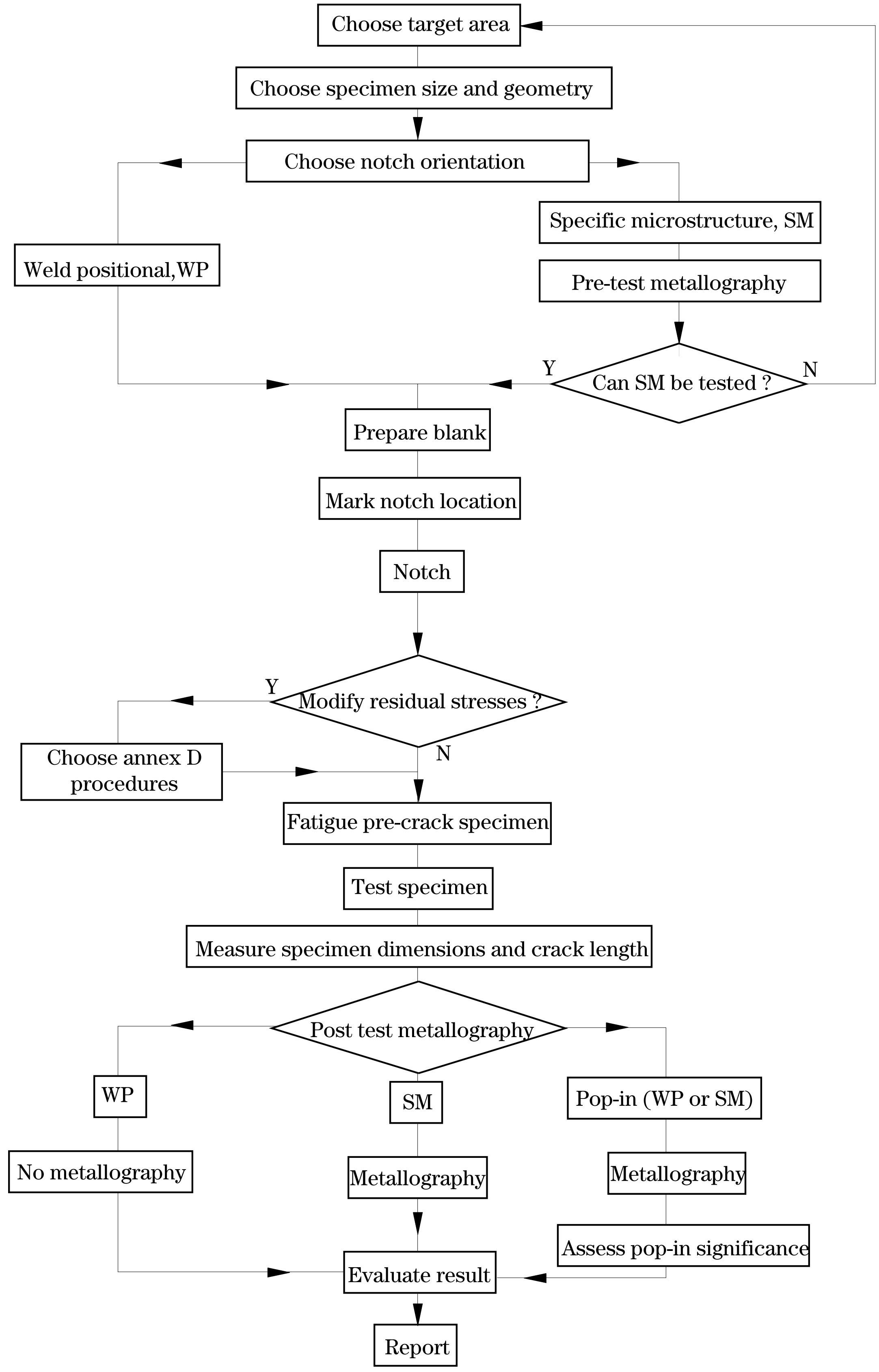
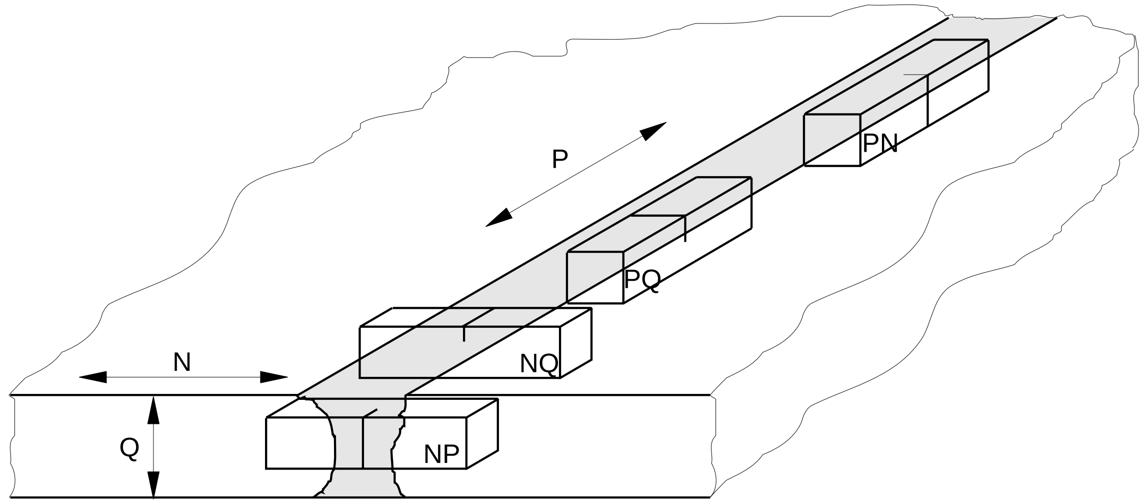


Figure 1. Test method flow chart for BS 7448 : Part 2



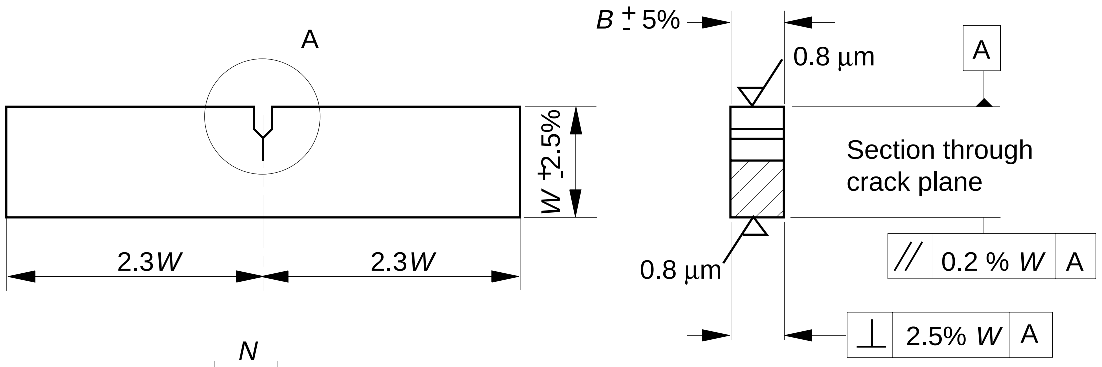
N = Normal to weld direction
P = Parallel to weld direction
Q = Weld thickness direction

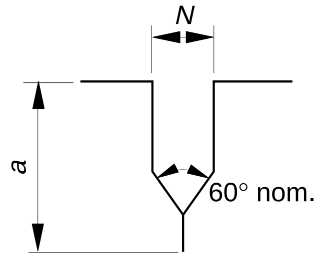
First letter: the direction normal to the crack plane
Second letter: the expected direction of crack propagation

A subscript X or Y is added to the N direction to indicate whether this direction is parallel or transverse to the primary grain flow direction in the parent material when testing the HAZ, e.g. if N is parallel to the primary grain flow direction, the NP specimen is defined as N_XP, and N_YP if the primary grain flow direction is perpendicular to N.

Specimen orientations NP and PN shall be referred to as through-thickness notched, whilst specimen orientations NQ and PQ shall be referred to as surface notched.

Figure 2. Crack plane orientation code for welded fracture toughness specimens (defined relative to weld direction)





Detail A

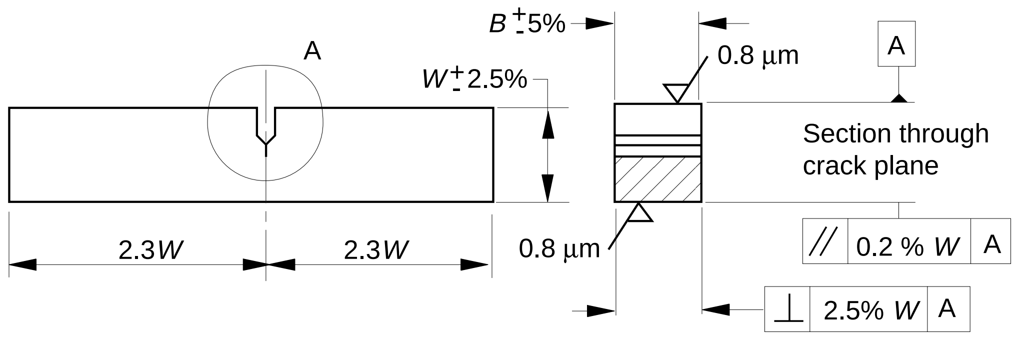
Width = W
Thickness = B = 0.5W
Loading span, S = 4W
Notch width = 0.065W max.

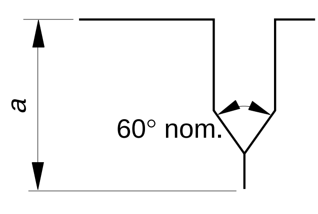
Specimen length straightness:
10%W along length, see fig. 4

Specimen side straightness:
2.5%W, see fig. 4

For nominal crack length, a = 0.45W to 0.70W
(see BS 7448 : Part 1 : 1991 and BS 7448 : Part 4 : 1997 as appropriate)

a) Rectangular section bend specimens





Detail A

Width = W
Thickness = B = 0.5W
Loading span, S = 4W
Notch width = 0.065W max.

Specimen length straightness:
10%W along length, see fig. 4

Specimen side straightness:
2.5%W, see fig. 4

For nominal crack length, a = 0.45W to 0.70W
(see BS 7448 :Part 1 : 1991 and BS 7448 : Part 4 : 1997 as appropriate)

b) Square section bend specimens

Figure 3. Proportional dimensions and tolerances for rectangular section bend specimens and square section bend specimens

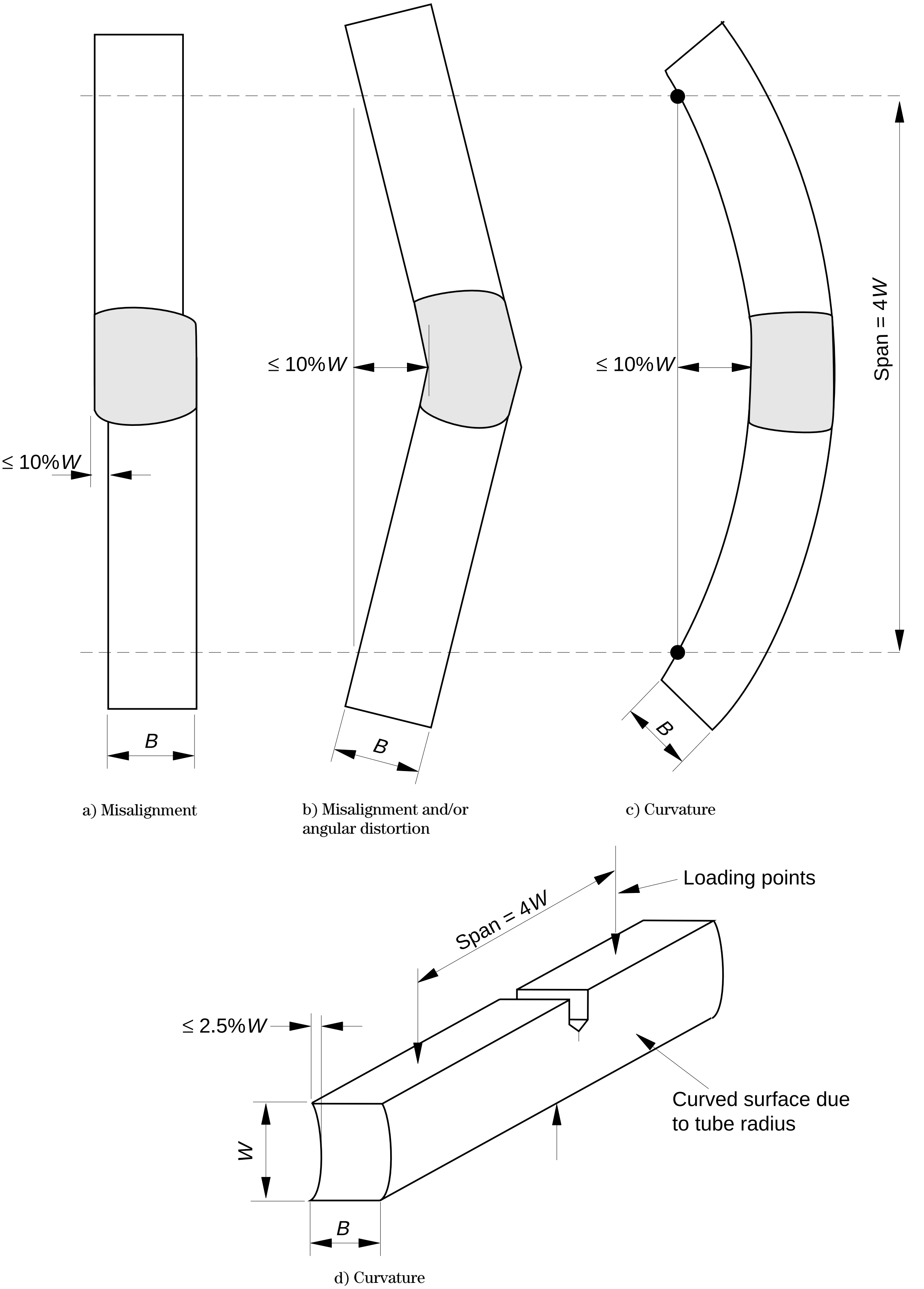
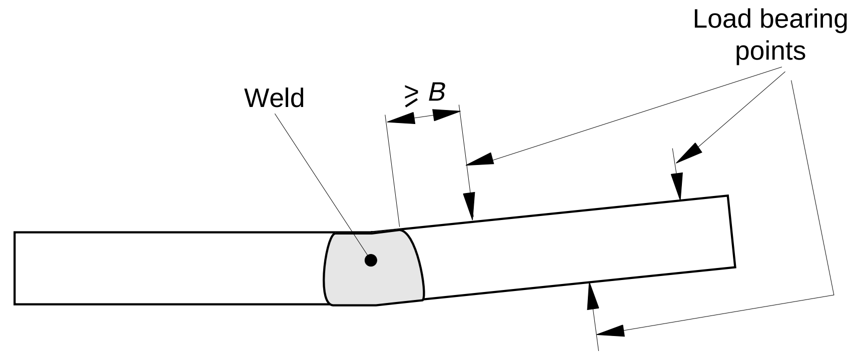
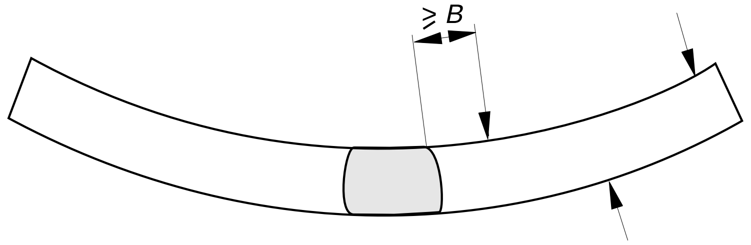


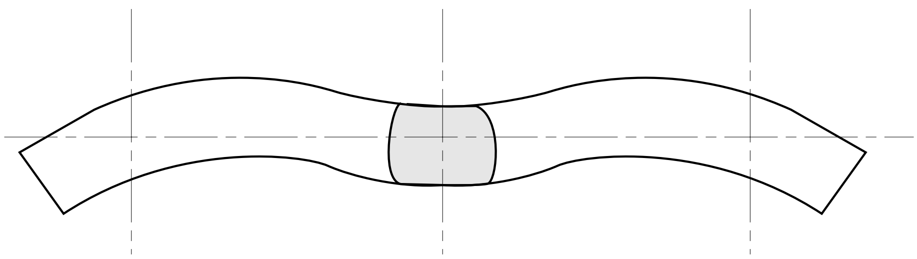
Figure 4. Acceptable tolerances for misalignment, distortion and curvature in single edge notch bend specimens



a) To reduce angular distortion



b) To reduce curvature of pipe specimen



c) Resultant 'gull wing' specimen from pipe section

Figure 5. Method for straightening bend specimen blanks

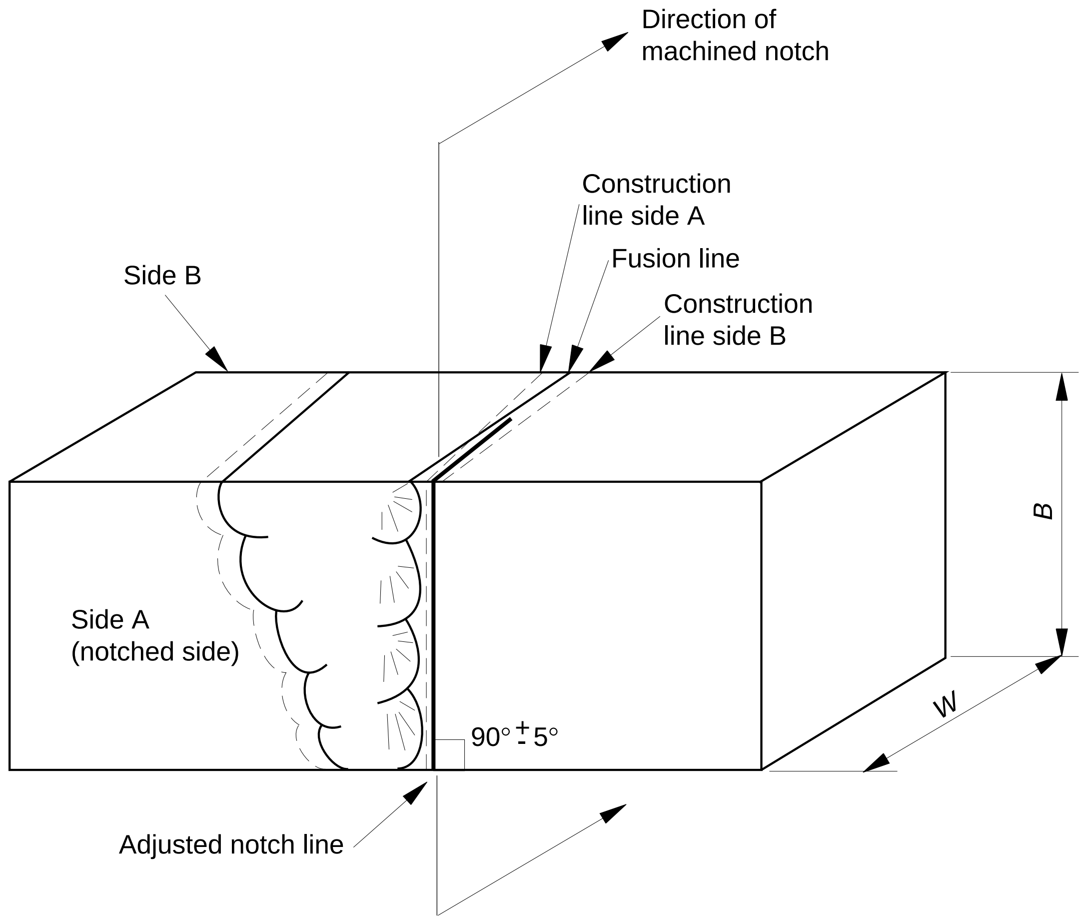


Figure 6. Notch placement procedure using construction lines in a through-thickness notched specimen

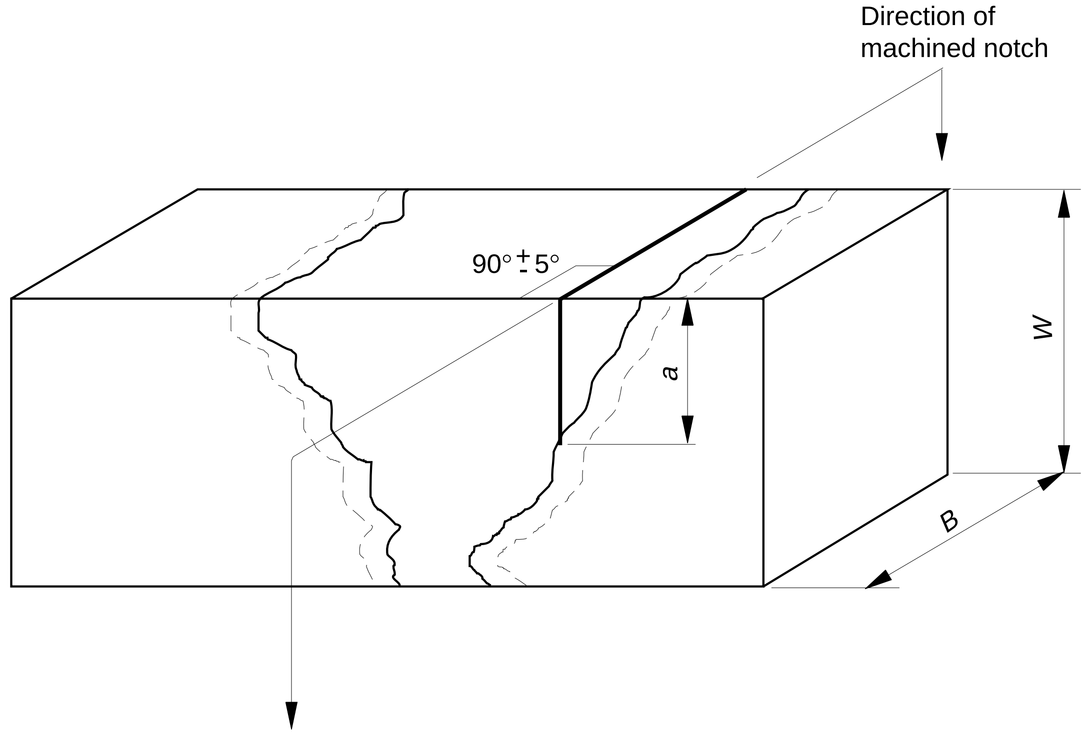


Figure 7. Notch placement procedure in a surface notched specimen

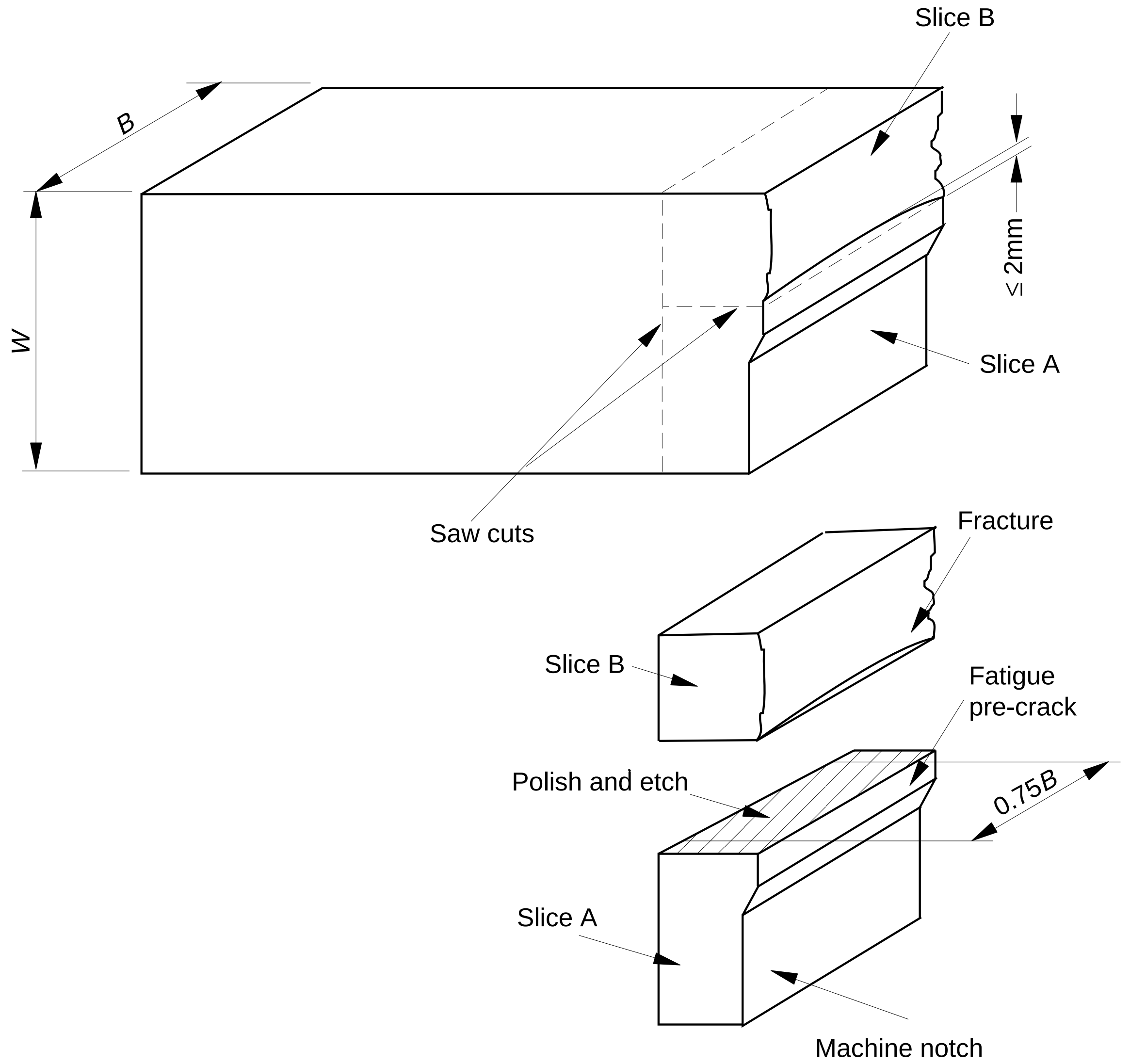


Figure 8. Post-test sectioning procedure to identify microstructure at fatigue crack in a through-thickness notched specimen

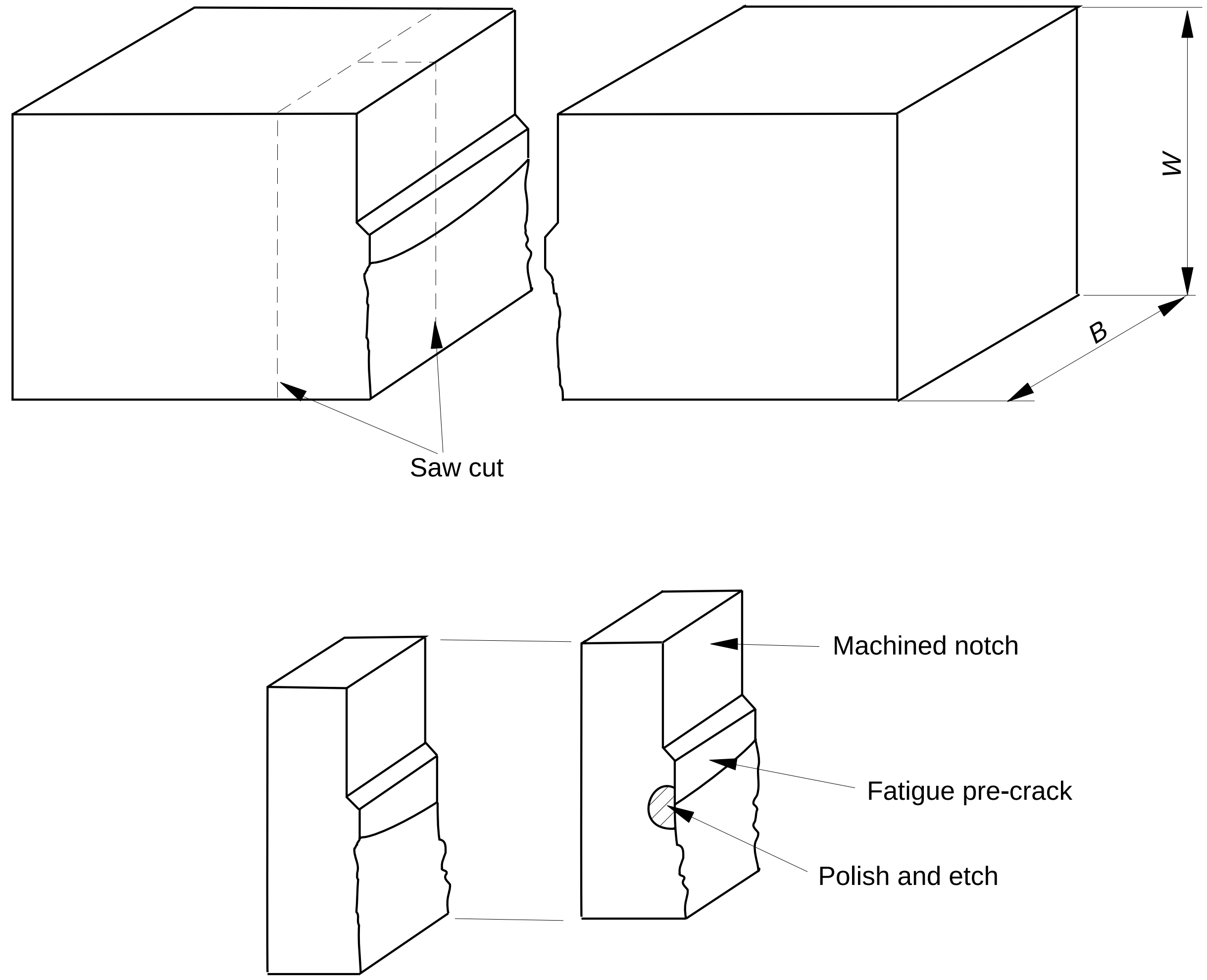


Figure 9. Post-test sectioning of a surface notched specimen

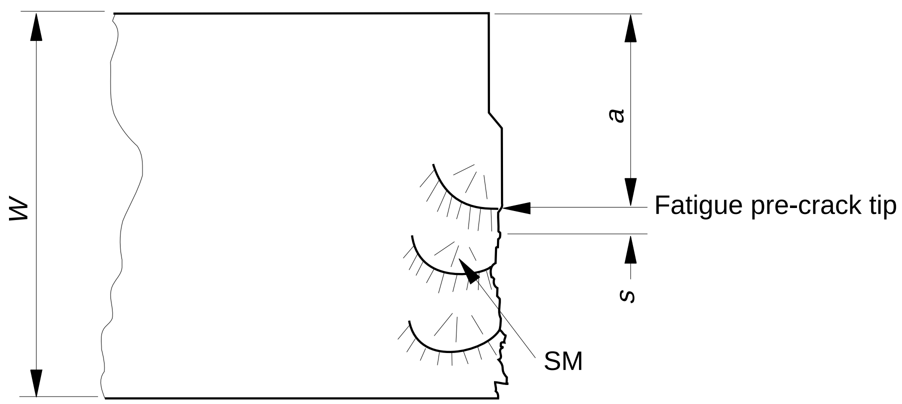


Figure 10. Measurement of *s* in an SM surface notched specimen

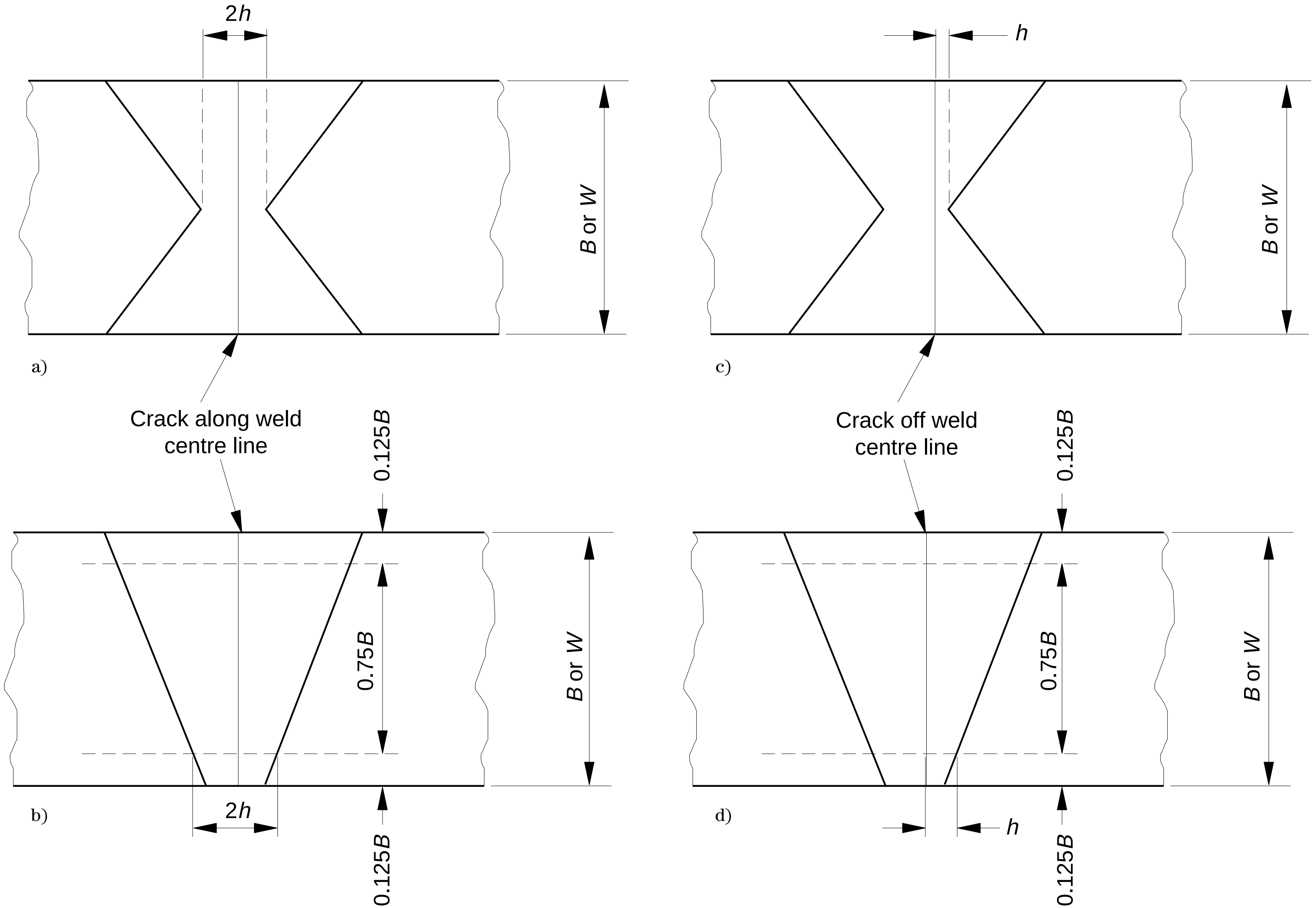


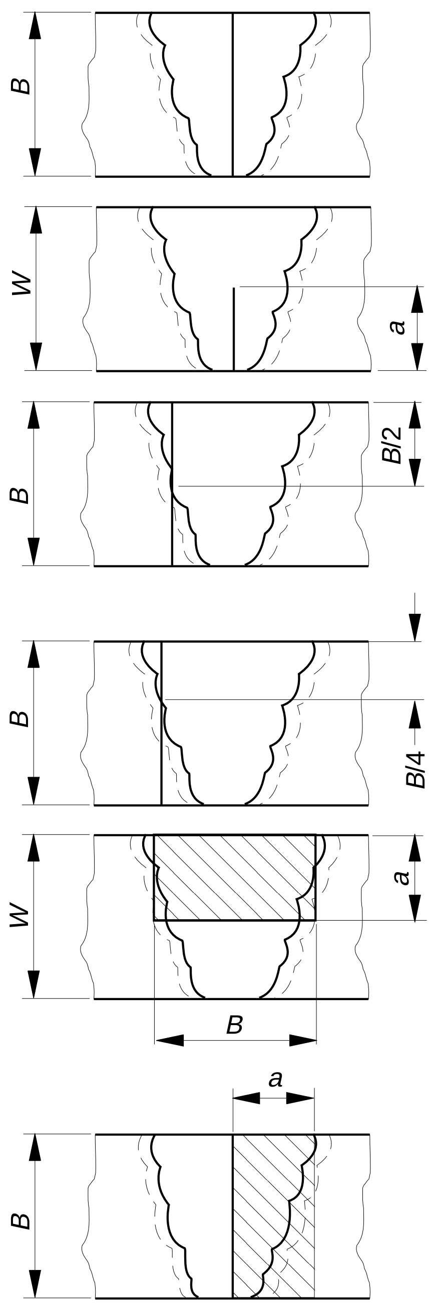
Figure 11. Definition of h and $2h$ in double and single sided welds

Annexes

Annex A (informative)

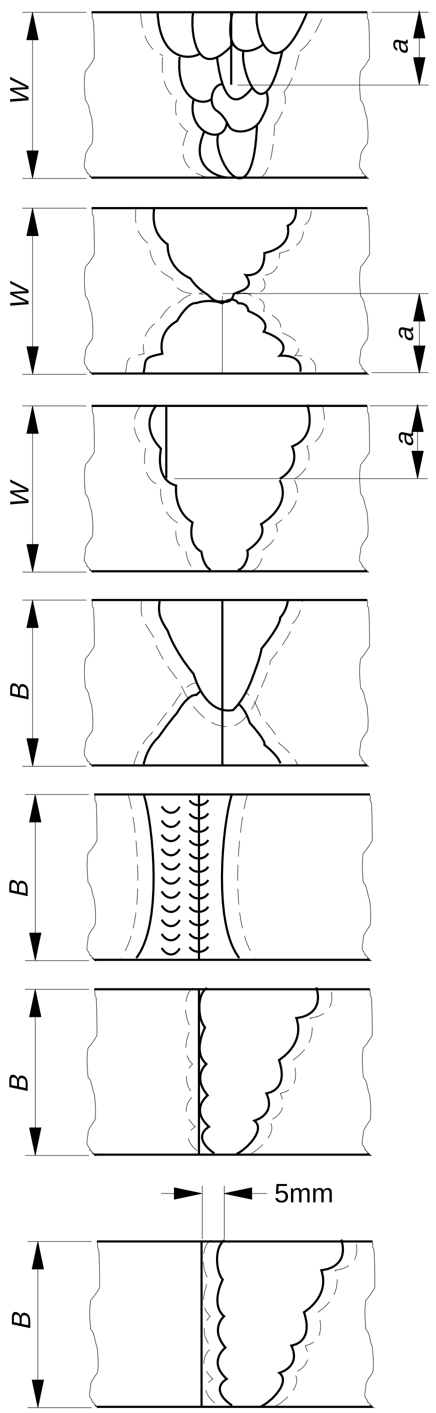
Examples of notch locations

Examples are given in this annex of typical locations which can be used when testing weld metal and HAZ with through-thickness and surface notched bend specimens. Figure A.1 shows weld positional (WP) notch locations, whilst figure A.2 shows specific microstructure (SM) notch locations.



	Orientation	Geometry	Notch location
(i)	NP	$B \times B$ or $B \times 2B$	Weld metal centre line
(ii)	NQ	$B \times B$	Weld metal centre line from weld root
(iii)	NP	$B \times B$ or $B \times 2B$	HAZ with notch intersecting fusion line at mid-thickness
(iv)	NP	$B \times B$ or $B \times 2B$	HAZ with notch intersecting fusion line at quarter thickness
(v)	PQ	$B \times B$	Transverse to weld
(vi)	PN	$B \times B$	Transverse to weld, weld centre line

Figure A.1 Examples of weld positional (WP) notch locations



	Orientation	Geometry	Notch location
(i)	NQ	$B \times B$	Columnar weld metal on weld centre line
(ii)	NQ	$B \times B$	Weld root of first side welded
(iii)	NQ	$B \times B$	GCHAZ adjacent to columnar weld metal
(iv)	NP	$B \times B$ or $B \times 2B$	Maximum volume of as-deposited columnar weld metal
(v)	NP	$B \times B$ or $B \times 2B$	Maximum volume of columnar weld metal
(vi)	NP	$B \times B$ or $B \times 2B$	Crack front to sample at least 15 % GCHAZ with a grain size > 50 mm (or 15 % HAZ adjacent to columnar weld metal)
(vii)	NP	$B \times B$ or $B \times 2B$	HAZ at fusion line + 5 mm

Figure A.2 Examples of specific microstructure notch locations

Annex B (informative)

Example of pre-test metallography

Pre-test metallography is necessary when SM testing is specified for the HAZ. Figures B.1 and B.2 give an example of the method of quantifying the amount of HAZ microstructure, in this case HAZ adjacent to columnar weld metal, present in a macrosection prepared for metallography. Figure B.2 shows how to prepare a map of the target microstructure identified in the macrosection (see figure B.1) within the central 75 % of specimen thickness. The individual lengths of SM (λ) along a line representing the idealized notch are summed to give the percentage SM present.

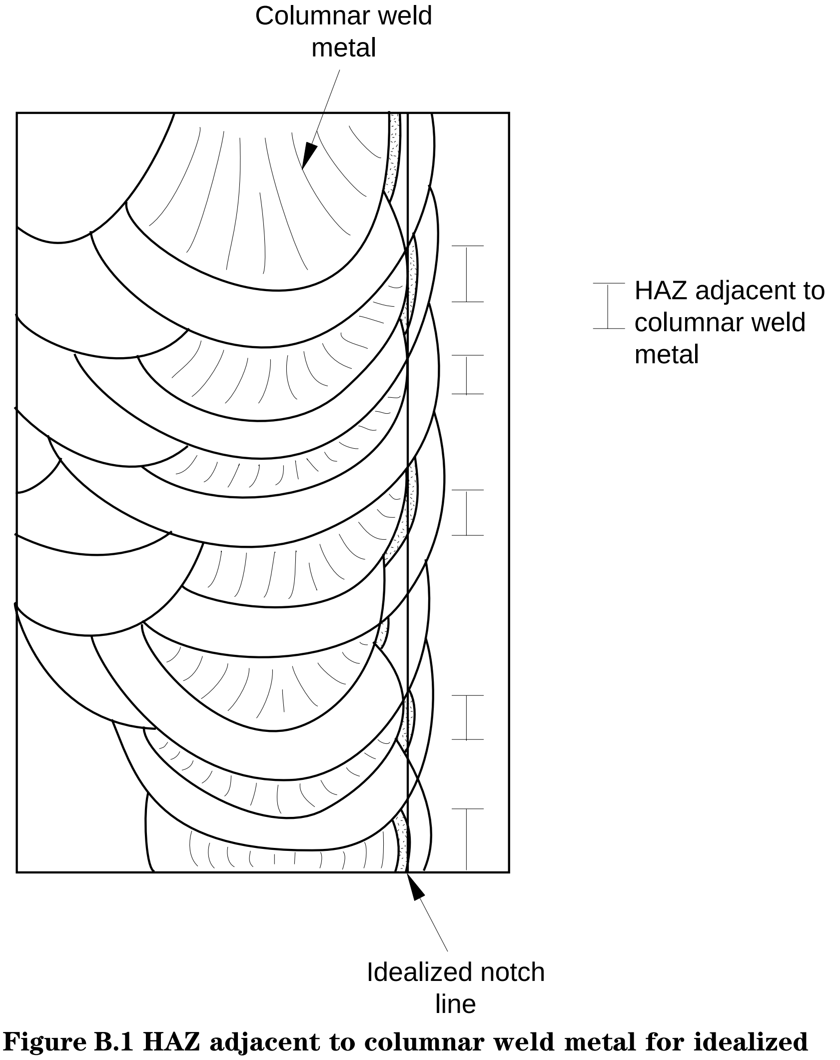
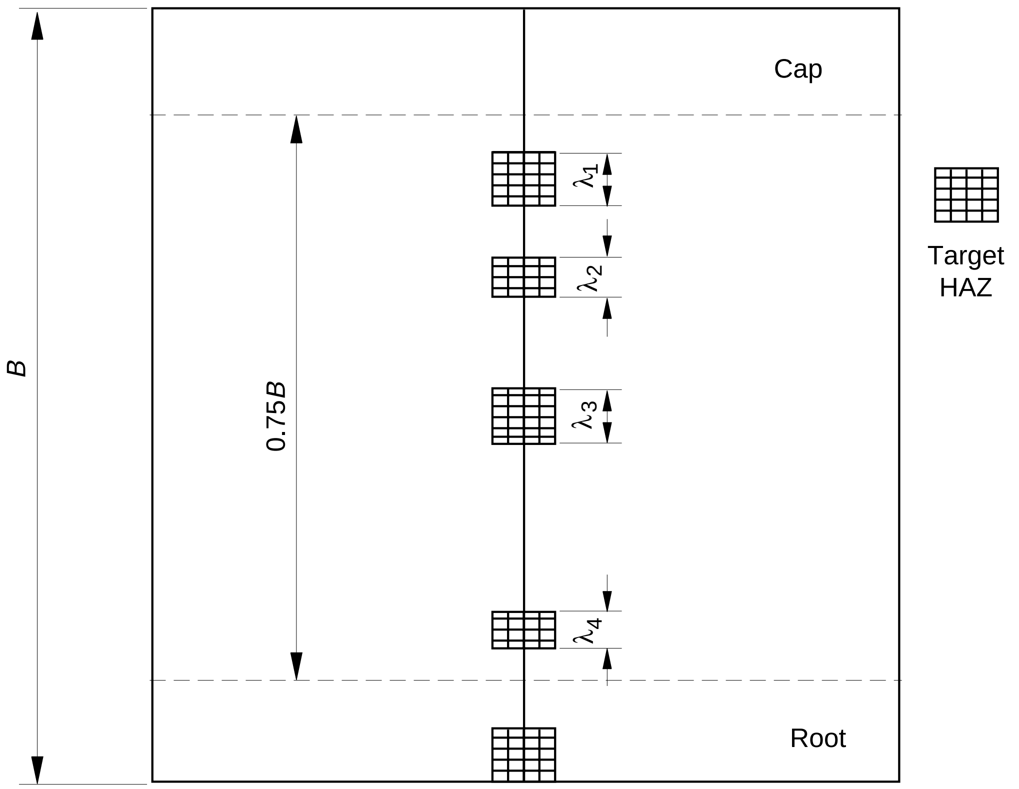


Figure B.1 HAZ adjacent to columnar weld metal for idealized notch line on macrosection



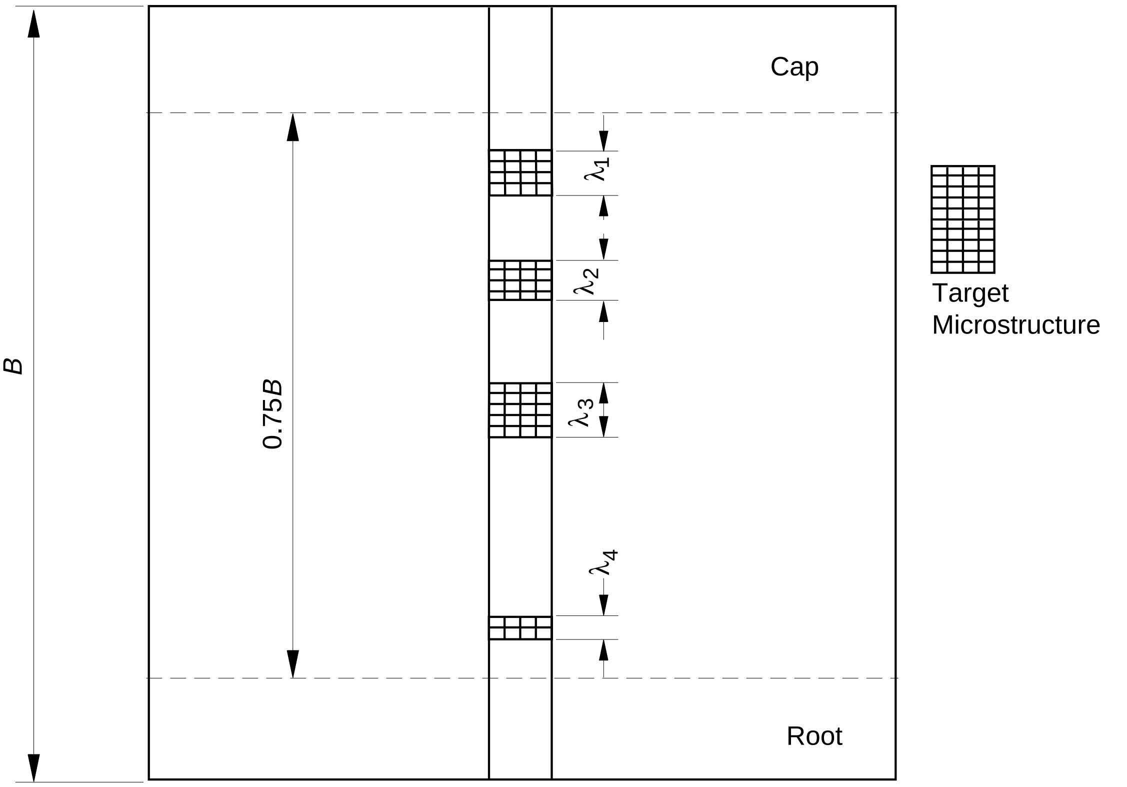
% specified microstructure (over middle 75 % of thickness)

$$= \frac{\sum_{\lambda_1}^{\lambda_n} \lambda}{0.75B} \times 100$$

Figure B.2 Microstructural map of HAZ adjacent to columnar weld metal

Annex C (informative)
Example of post-test metallography

Post-test metallography is necessary when SM testing is specified to confirm that the target microstructure was present close to the fatigue crack tip. Figure C.1 shows mapping of the lengths of target microstructure (λ) in this case grain coarsened HAZ, present in a macrosection removed from a through-thickness notched specimen, e.g. slice A in figure 8.



% specified microstructure (over middle 75 % of thickness)

$$= \frac{\sum_{\lambda_1}^{\lambda_n} \lambda}{0.75B} \times 100$$

Figure C.1 Post-test microstructural map at the crack tip of a specimen notched into the HAZ in a carbon manganese steel

Annex D (normative)
Residual stress modification and precracking technique

D.1 General

One of the following techniques, as given in **D.2**, **D.3** or **D.4**, shall be used when testing as-welded or partially stress relieved specimens. The technique used shall be described when reporting the test results, and shall include any new or previously documented evidence that the residual stresses have been reduced to low uniform levels, as specified in **D.5**.

D.2 Local compression

Experience of testing specimens representing full section thickness welds in as-welded and partially stress relieved conditions indicates that the application of local compression to the ligament below the machine notch is often sufficient to reduce the welding residual stresses to low and uniform levels and result in the growth of an acceptably straight fatigue precrack ([1], [2] and [3]). Furthermore, the reduction in residual stress ensures that any residual stress remaining will have a minimal effect on fracture toughness.

Local compression is applied prior to fatigue precracking and side grooving across 88 % to 92 % of the ligament ($W - a$) in front of the machined notch, and shall encompass the notch tip. Indentation is carried out using hardened steel platens, to produce a total plastic strain of up to 1 % of the specimen thickness (see notes 1 and 2). Guidance on the forces that need to be applied are indicated in figure D.1. Depending on the thickness (B), local compression may be applied from one side only or, up to 0.5 % B to each side of the specimen simultaneously, (see figure D.1).

Multiple indents may be used with lower compression forces. For this case, the platens shall have no dimension in the plane of the indent less than 0.5 B, see figure D1. In addition, the final indent shall be made nearest to the notch tip.

A number of force applications may be necessary to achieve the required plastic deformation. This shall be measured to ± 0.025 mm or ± 0.1 % B, whichever is larger.

For specimens that have been locally compressed, the dimension B used for the calculation of fatigue force and stress intensity factor shall be B in the region of the notch measured after local compression.

NOTE 1. Local machining of the ligament to be compressed on both sides of the specimen may be necessary to ensure a smooth bearing surface for the platen and to achieve uniform deformation.

Any bulging of the back face of the ligament leading to distortion in three point bend specimens at the loading point shall be removed by machining.

NOTE 2. Experience indicates that 1 % B total deformation may be too much for some welds and materials, and straighter crack fronts may be obtained with less. Trials may be necessary to establish the optimum conditions.

NOTE 3. Local compression is normally unnecessary for welds which have been stress relieved by post weld heat treatment.

Post weld heat treatment shall only be carried out on the specimen if the final condition of the weld is in the heat treated condition. Any heat treatment shall be completed prior to fatigue precracking.

D.3 Reversed bending

The specimen is loaded to compress the machined notch (i.e. reverse bending of the specimen), before conventional fatigue precracking [3]. The aim is to deform plastically the material at the notch root and produce a uniform tensile residual stress there. This is done using a single cycle of bending load applied to the notched side of a single edge notch bend specimen. The maximum value of this 'reversed bending load' is determined from the following equation:

$$K_{\mathrm{rb}} = LR_{\mathrm{p0.2}}\sqrt{\frac{8\omega_{\mathrm{rb}}}{\pi}}$$

where

K_{rb} is the reverse bend stress intensity factor;

L is the notch constraint factor (typically 2.3 for a rectangular specimen);

ω_{rb} is the plastic zone size resulting from reverse bending.

Experience indicates that reverse bending is not always successful and does not reduce significantly the level of residual stress at the fatigue crack tip position [4]. The presence of residual stresses can affect the test result.

D.4 Stepwise high *R*-ratio

In the stepwise high R-ratio technique [5], fatigue precracking consists of two steps, each at different fatigue stress ratios (R). For the first step, the stress ratio $R = 0.1$ is used (i.e. the conventional R value) until the fatigue precrack has grown to a length of about 1 mm. In the second step, R is increased to 0.7 and the fatigue precrack grown to the desired length. The same K_{f} is used in both steps.

NOTE. Use of $R > 0.1$ is inconsistent with the fatigue precracking requirements in **6.4** of BS 7448 : Part 1 : 1991.

Although experience indicates that the high R-ratio technique can result in acceptably straight fatigue precracks, it does not reduce significantly the residual stresses in the ligament ($W-a$) ahead of the fatigue crack tip and this can affect the test result [4]. Nevertheless, the technique has been used as an alternative to local compression when testing thick section high strength steels and when the forces necessary for local compression are not readily attainable.

D.5 Evidence of low uniform residual stresses

D.5.1 *General*

The results for all specimens meeting the requirements of this standard shall include documentary evidence that any residual stresses ahead of the precrack tips are at low uniform levels. Where such evidence is not available for the particular combination of technique (**D.2**, **D.3** or **D.4**), metal and weld used (see **D.5.3**), a sacrificial test to indicate the level of any residual stresses shall be carried out on a representative specimen as described in **D.5.2**.

D.5.2 ***Sacrificial test***

D.5.2.1 Regardless of the technique used to prepare the specimen for the sacrificial test (**D.2**, **D.3** or **D.4**), the initial fatigue precrack shall be extended by additional fatigue cracking with $R \leq 0.1$, and F_f in accordance with **6.4** of BS 7448 : Part 1 : 1991, until the average of the two crack length measurements on the surfaces of the specimen, measured to $\pm$ 0,05 mm, is $\geq \{a + 0.4\ (W - a)\}$.

D.5.2.2 The specimen shall be broken open to reveal the fatigue crack surfaces using the procedures in **8.7.1** of BS 7448 : Part 1 : 1991.

D.5.2.3 The weighted nine-point average crack length to the tip of the original fatigue crack (a_o) shall be measured as specified in **8.7.2** of BS 7448 : Part 1 : 1991. Similar measurements shall be made of the weighted nine-point average crack length to the tip of the additional fatigue crack (a_{af}).

D.5.2.4 Residual stresses in the uncracked ligament ahead of the notch tip in the specimen shall be deemed to be acceptably low and uniform provided that:

a) the values of a_o/W are within the acceptable range for the appropriate specimen in BS 7448 : Part 1 or Part 4;

b) $a_{af} \geq \{a_o + 0.4\ (W - a_o)\}$;

c) for K_{Ic} tests on three point bend and compact specimens, and CTOD (or δ) and J tests on compact specimens, the difference between any two of the nine-point crack length measurements for a_o is $\leq$ 10 % a_o, and similarly, for a_{af} is $\leq$ 10 % a_{af} ;

d) for CTOD (or δ) and J tests on three point bend specimens, the difference between any two of the inner seven crack length measurements for a_o is $\leq$ 20 % a_o, and similarly, for a_{af} is $\leq$ 20 % a_{af}.

D.5.3 ***Previously documented evidence***

When the local compression technique (**D.2**) has been used, and the crack front straightness requirements for a_o in **D.5.2.4** have been met, reference [4] shall be accepted as representing the required documentary evidence of low uniform residual stresses in specimens from multi-pass arc welds in carbon manganese steels.

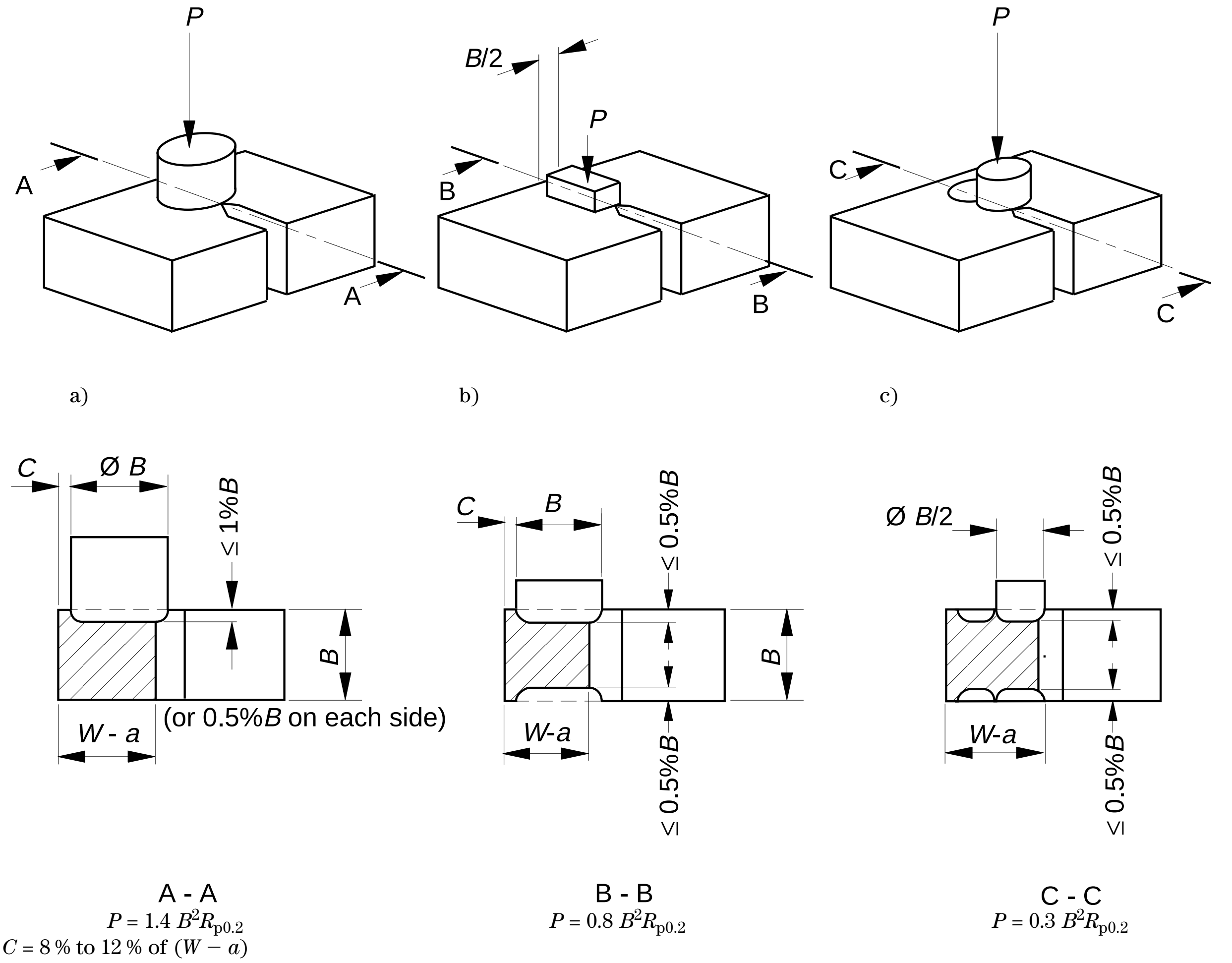


Figure D.1 Alternative local compression treatments

Annex E (normative)
Assessment of pop-in

E.1 General

This procedure shall be used to assess the acceptability of pop-ins classed as significant according to **11.4**.

The first step is to assess the significance of the pop-in in accordance with **9.1**, **9.3** and **9.4** of BS 7448 : Part 1. If the pop-in is assessed as significant according to Part 1, it is also significant according to the requirements of this standard and post-test fractography and metallography is not required. However, if the pop-in is assessed as acceptable according to Part 1, the actual significance, with respect to this Part can be determined from the fractographic and metallographic assessment procedures described in **E.2** to **E.5**.

E.2 Fractography

Both fracture faces shall be carefully examined for evidence of an arrested brittle crack generally in the plane of the fatigue crack, and the maximum crack extension (Δa_{pop}) shall be measured, (see figure E.1). Where no evidence of such an arrested brittle crack can be found, the significance of the pop-in shall be assessed in accordance with **9.1**, **9.3** and **9.4** of BS 7448 : Part 1.

NOTE. Pop-in can be caused by an arrested crack running perpendicular to the plane of the fatigue precrack; this is sometimes referred to as a 'split'. The fracture toughness at pop-in caused by a split needs to be reported. However, the assessment of the structural significance of the split is outside the scope of this standard.

E.3 Sectioning and metallography

One or both fracture surfaces containing the arrested brittle crack shall be examined with optical and/or scanning electron microscopy, to identify the primary fracture initiation position. When the crack tip is located in the HAZ, the fracture surface adjacent to the weld shall be examined. After marking the initiation position, a metallographic section shall be taken through the initiation point on a plane perpendicular to the fatigue crack plane, as illustrated in figure E.2 for a through-thickness notched specimen, and figure E.3 for a surface notched specimen. The sections shall be polished and etched according to usual metallographic practices for microstructural examination.

E.4 Assessment

The metallographic section taken from a through-thickness notched specimen (see figure E.4) shall be examined and the length of the specific microstructure parallel to the crack front at initiation (d_1) shall be measured. The lengths of similar microstructures present in the section within the central 75 % of B (or B_N, in the case of sidegrooved specimens), but not intersected by the crack front shall be measured and the maximum individual length d_2, recorded (see figure E.4). If the section is beyond the fatigue crack tip, a further section behind the fatigue crack tip may be necessary to measure d_2.

The metallographic section taken from a surface notched specimen (see figure E.5) shall be examined and the total length (d_1) of the microstructural region in which the pop-in initiated, shall be measured. This length (d_1) shall only include the microstructural region ahead of the fatigue crack tip, (see figure E.5). (More than one section may be taken to assess the dimension d_1).

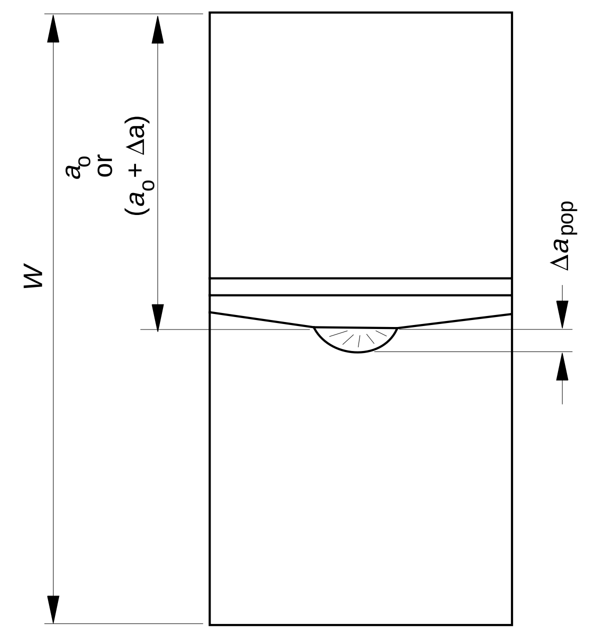


Figure E.1 Measurement of Δa_{pop}

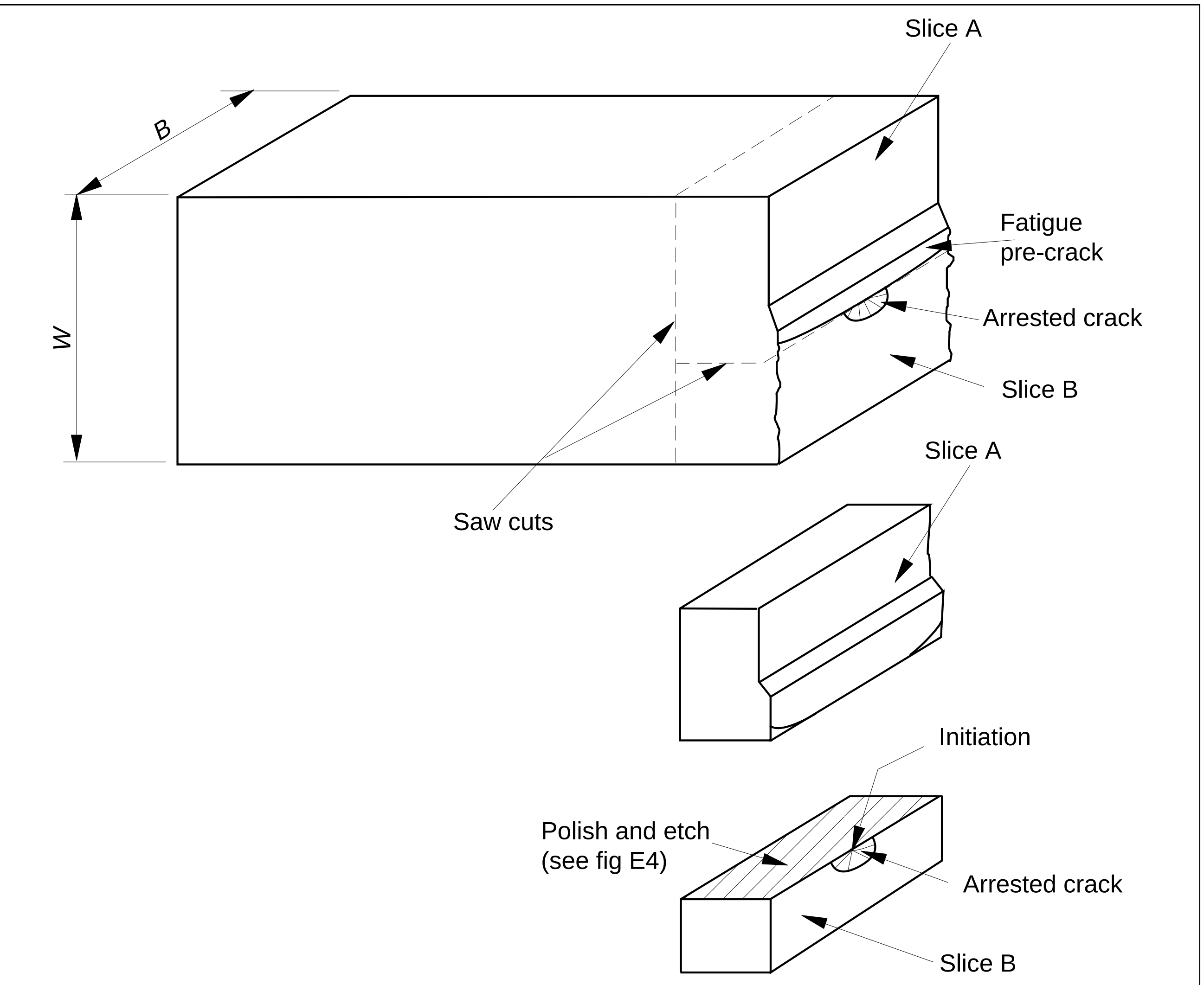


Figure E.2 Post-test sectioning procedure for identifying fracture initiation microstructure in a through-thickness notched specimen

E.5 Pop-in significance

All pop-ins shall be considered significant unless it can be demonstrated otherwise by metallographic examination. Values of CTOD and J measured at the first pop-in event shall be designated δ_{pop} or J_{pop}, as appropriate.

Following metallographic examination, a pop-in shall not be considered significant if:

a) d_n % F_1, calculated in accordance with clause **9** of BS 7448 : Part 1 : 1991, is less than 5 % and $d_1 \geq d_2$, for a through-thickness notched specimen; or

b) d_n % F_1 is less than 5 % and $\Delta a_{pop} \leq d_1$ for a surface notched specimen.

The pop-in shall be considered significant when $d_2 > d_1$ or $d_1 > \Delta a_{pop}$ because a larger pop-in may have occurred if more of the brittle microstructure had been sampled or had been present ahead of the crack tip. Further tests may be necessary to confirm or reject this possibility.

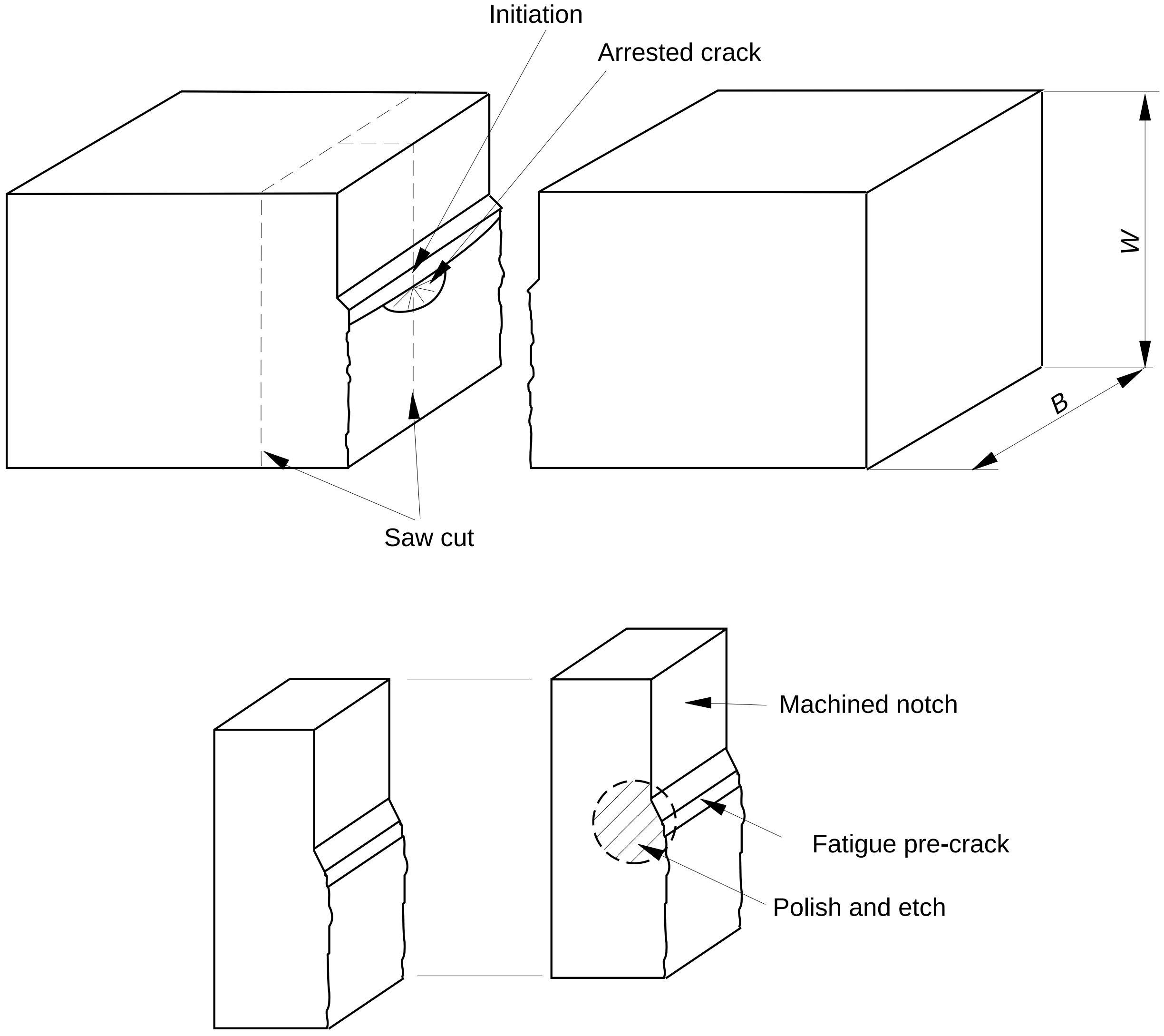
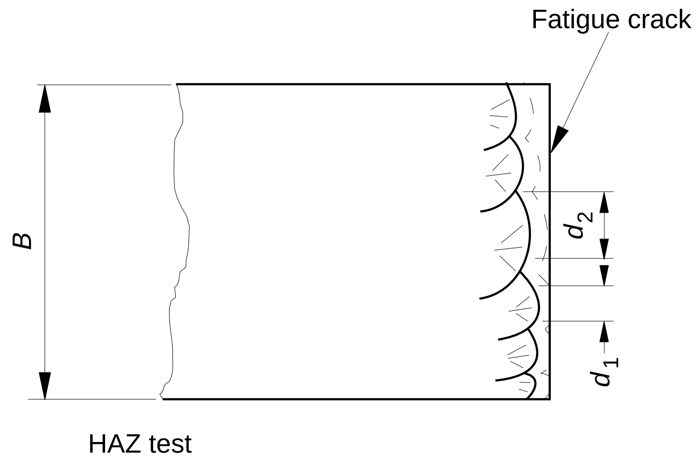
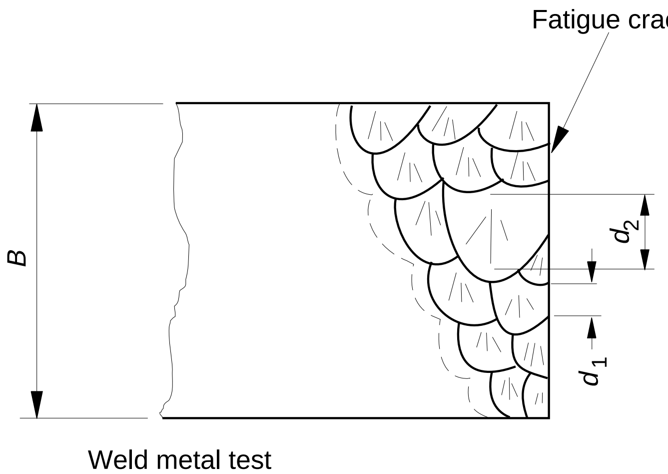


Figure E.3 Post-test sectioning for identifying fracture initiation microstructure in a surface notched specimen



Fatigue crack cuts through HAZ d_1 but not HAZ d_2



Fatigue crack cuts through weld bead d_1 but not weld bead d_2

Figure E.4 Measurement of d_1 (along crack front) and d_2 (not along crack front) microstructure in section taken from through-thickness notched specimens (slice B in figure E.2)

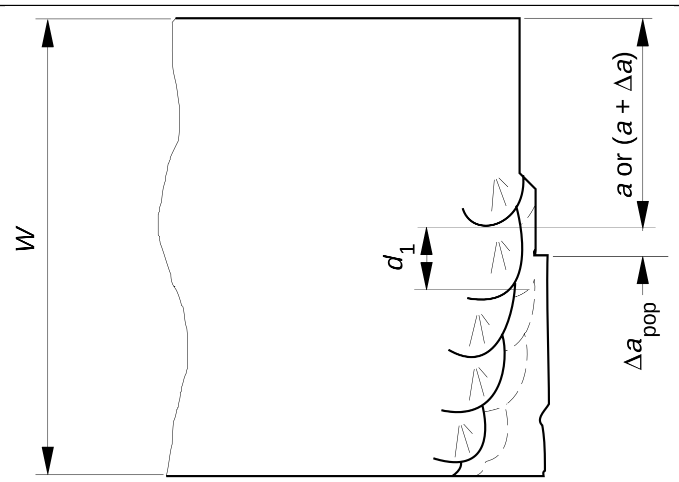


Figure E.5 Measurement of microstructure d_1 and Δa_{pop} in section taken from a surface notched specimen, see figure E.3 (example given for HAZ)

blank

List of references (see clause 2)

Normative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 7448	*Fracture mechanics toughness tests*
BS 7448 : Part 1 : 1991	*Method for determination of K_{Ic}, critical CTOD and critical J values of metallic materials*
BS 7448 : Part 4[3)]	*Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials*

Informative references

BSI publications

BRITISH STANDARDS INSTITUTION, London

BS 499	*Welding terms and symbols*
BS 499 : Part 1 : 1991	*Glossary for welding, brazing and thermal cutting*

Other references

[1] DAWES, M. G. Fatigue precracking weldment fracture mechanics specimens. *Metal Construction & British Welding Journal*, February 1971, pp.61-65.
[2] TOWERS, O. L. and DAWES, M. G. Welding Institute research on the fatigue precracking of fracture toughness specimens. *Elastic plastic fracture test methods*. ASTM STP 856, 1985, pp.23-46.
[3] MACHIDA, S., MIYATA, T., TOYOSADA, M. and HAGIWA, Y. Study of methods for CTOD testing of weldments. *Fatigue and fracture testing of weldments*. ASTM STP 1058, 1990, pp.142-156.
[4] REEMSYNDER, H. S., PISARSKI, H. G. and DAWES, M. G. Residual stresses and fatigue precracking techniques for weldment fracture toughness specimens. *Journal of Testing and Evaluation*, November 1991, pp.416-423.
[5] KOÇAK, M., SEIFERT, K., YAO, S. and LAMPE, H. Comparison of fatigue precracking methods for fracture toughness testing of weldments. Proc. Int. Conf. Welding 90 — Technology, Material, Fracture — GKSS, Geesthacht, Germany, October 1990. i.i.t.t International, France.

3) In preparation.

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