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Method of test for determination of fracture toughness in metallic materials using single edge notched tension (SENT) specimens

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Contents

Summary of pages

This document comprises a front cover, an inside front cover, pages i to ii, pages 1 to 22, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI Standards Limited, under licence from The British Standards Institution, and came into effect on 1 December 2014. It was prepared by Subcommittee ISE/101/4, *Toughness testing*, under the authority of Technical Committee ISE/101, *Test methods for metals*. A list of organizations represented on these committees can be obtained on request to their secretary.

Information about this document

This standard has been developed primarily to meet the needs of the steel pipeline industry where this method has been used to determine the fracture toughness of girth welds experiencing plastic straining during installation.

Hazard warnings

WARNING. This British Standard calls for the use of substances and/or procedures that can be injurious to health if adequate precautions are not taken. It refers only to technical suitability and does not absolve the user from legal obligations relating to health and safety at any stage.

Use of this document

It has been assumed in the preparation of this British Standard that the execution of its provisions will be entrusted to appropriately qualified and experienced people, for whose use it has been produced.

Presentational conventions

The provisions of this standard are presented in roman (i.e. upright) type. Its methods are expressed as a set of instructions, a description, or in sentences in which the principal auxiliary verb is "shall".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

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.

1 Scope

This British Standard gives methods for determining fracture toughness in metallic materials in terms of δ (crack tip opening displacement, CTOD) and J (experimental equivalent of the J-integral) using single edge notched tension (SENT) specimens.

This British Standard gives a method for determining fracture toughness as a resistance to ductile crack extension (R-curve). A method for single point determination of fracture toughness is also given. The method uses specimens which have been notched and fatigue pre-cracked into parent metal, weld metal or heat affected zone (HAZ). The specimens are loaded in tension, and the force and crack mouth opening displacement are recorded.

NOTE Methods to evaluate the suitability of a weld for notch placement within the target area and, where appropriate, to evaluate the effectiveness of the fatigue crack in sampling these areas are given in BS EN ISO 15653.

2 Normative references

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

BS EN ISO 15653:2010, *Metallic materials – Method of test for the determination of quasistatic fracture toughness of welds*

ISO 12135:2002, *Metallic materials – Unified method of test for the determination of quasistatic fracture toughness*

3 Terms, definitions and symbols

For the purposes of this British Standard, the following terms, definitions and symbols apply.

3.1 Terms and definitions

3.1.1 blunting

apparent crack extension not associated with the creation of new fracture surface prior to the onset of unstable crack extension, pop-in or slow stable crack extension and occurring within the same plane as the fatigue pre-crack

3.1.2 target area

intended fatigue pre-crack tip position within the parent metal, weld metal or heat affected zone (HAZ)

3.1.3 pop-in

abrupt discontinuity in the force versus displacement record, indicated by a sudden increase in displacement and, generally, a sudden decrease in force, subsequent to which displacement and force increase to above their previous values

3.1.4 sample

un-notched blank cut from the source material

3.1.5 specimen

machined and notched sample ready for testing

3.2 Symbols

For the purposes of this British Standard, the symbols given in BS EN ISO 15653 and ISO 12135 apply, together with the following:

a	crack length, in millimetres (mm);
a_0	initial crack length, in millimetres (mm);
B	specimen thickness, perpendicular to the width, in millimetres (mm);
B_N	specimen thickness after side-grooving, in millimetres (mm);
E	modulus of elasticity, in megapascals (MPa);
H	distance between clamped grips, in millimetres (mm);
J	J-integral fracture toughness, in kilojoules per metre squared or newtons per millimetre (kJ/m^2 or N/mm);
L_c	gauge length in a pin-loaded SENT specimen, in millimetres (mm);
P	nominal force in a SENT specimen, in newtons (N);
$R_{p0.2b}$	0.2% offset yield strength of the parent metal at the temperature of the fracture toughness test, in megapascals (MPa);
$R_{p0.2w}$	0.2% offset yield strength of the weld metal at the temperature of the fracture toughness test, in megapascals (MPa);
V_0	crack mouth opening displacement (CMOD), in millimetres (mm);
V_1, V_2	clip gauge displacements, in millimetres (mm);
V_{e1}, V_{e2}	elastic components of clip gauge displacement, in millimetres (mm);
V_{p1}, V_{p2}	plastic components of clip gauge displacement, in millimetres (mm);
W	specimen width, measured in the direction of the notch, in millimetres (mm);
δ	crack tip opening displacement (CTOD), in millimetres (mm);
ν	Poisson's ratio;
σ	nominal stress in a pin-loaded SENT specimen, in newtons per millimetre (N/mm^2);
Δa	sum of stable crack extension and crack tip blunting, in millimetres (mm).

4 Principle

A test sample is cut from the source material. The sample is machined and notched to provide a test specimen with the tip of the notch located in either the parent metal, the weld metal or the HAZ.

A fatigue crack is extended from the notch tip into the target area by applying a controlled alternating force to the specimen in bending. The specimen is then tested in tension by clamping or by pin-loading the specimen in the grips of a tensile test machine.

The force and clip gauge displacement are continuously recorded during the test. To construct a resistance curve a number of identical specimens are tested to different displacements and then unloaded. These data, together with measurements of specimen and crack dimensions, are used to determine fracture toughness and crack extension for the resistance curve. Alternatively, it is possible to test a single specimen to obtain a value of fracture toughness.

If specified by the customer, post-test metallography is performed to confirm that the crack tip was located in the target weld feature and/or microstructure and to determine the microstructure through which crack extension has taken place.

NOTE A flowchart illustrating how to use this British Standard is given in Figure 1.

5 Test sample and test specimen preparation

5.1 Test sample

A blank sample shall be cut from the test source material.

NOTE The choice of specimen design should take into consideration the likely outcome of the test, any preference for J or CTOD fracture toughness values, the crack plane orientation of interest and the quantity and condition of the material available.

5.2 Test specimen

A test specimen shall be prepared from the sample. The SENT test specimen configuration shall be as shown in Figure 2a) or Figure 2b). The cross-section dimensions shall be expressed as the specimen thickness (B) × width (W). The W/B ratio of the test specimen shall be between 0.5 and 2, as illustrated in Figure 3.

Figure 1 **Flowchart showing how to use the standard**

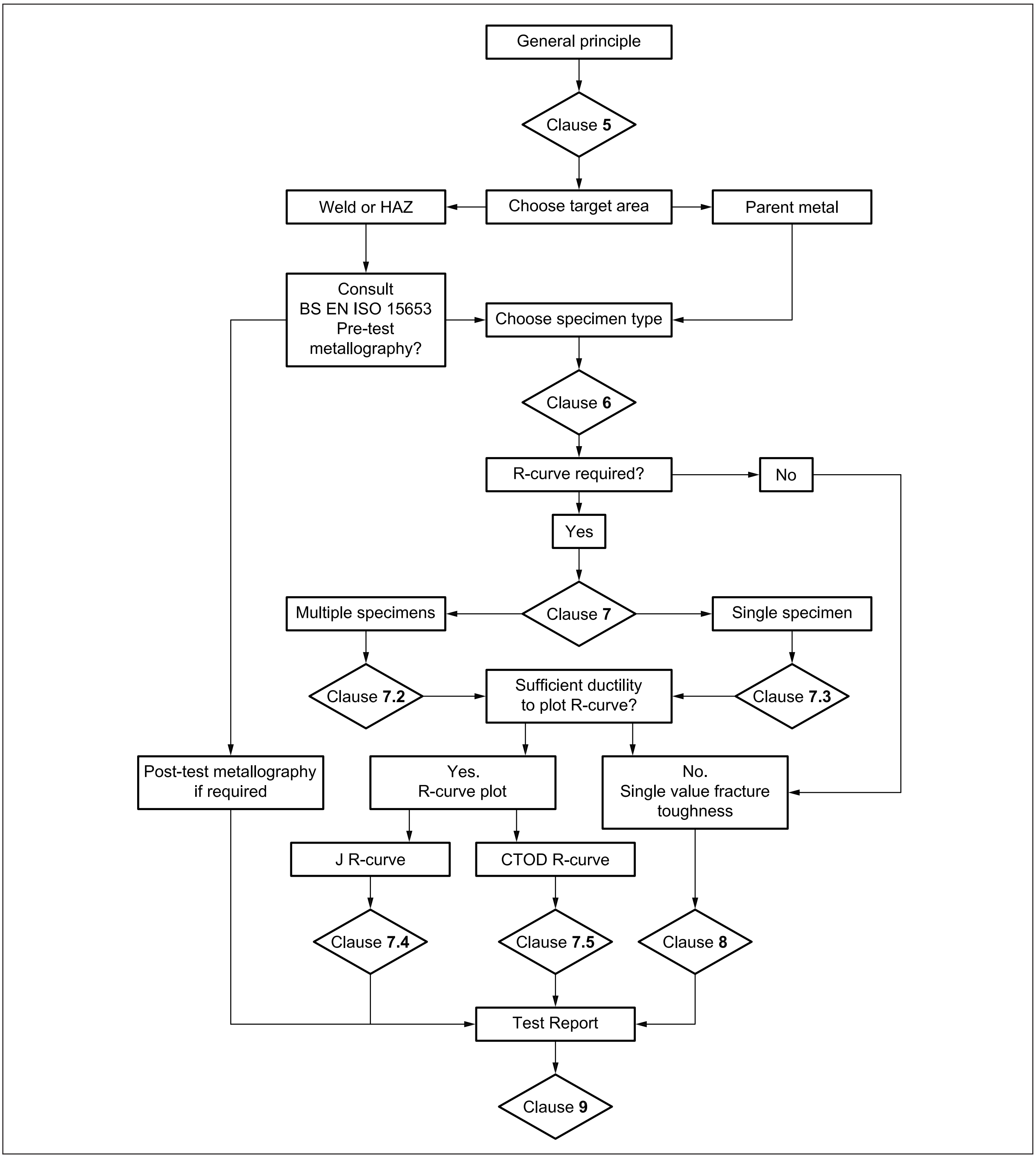
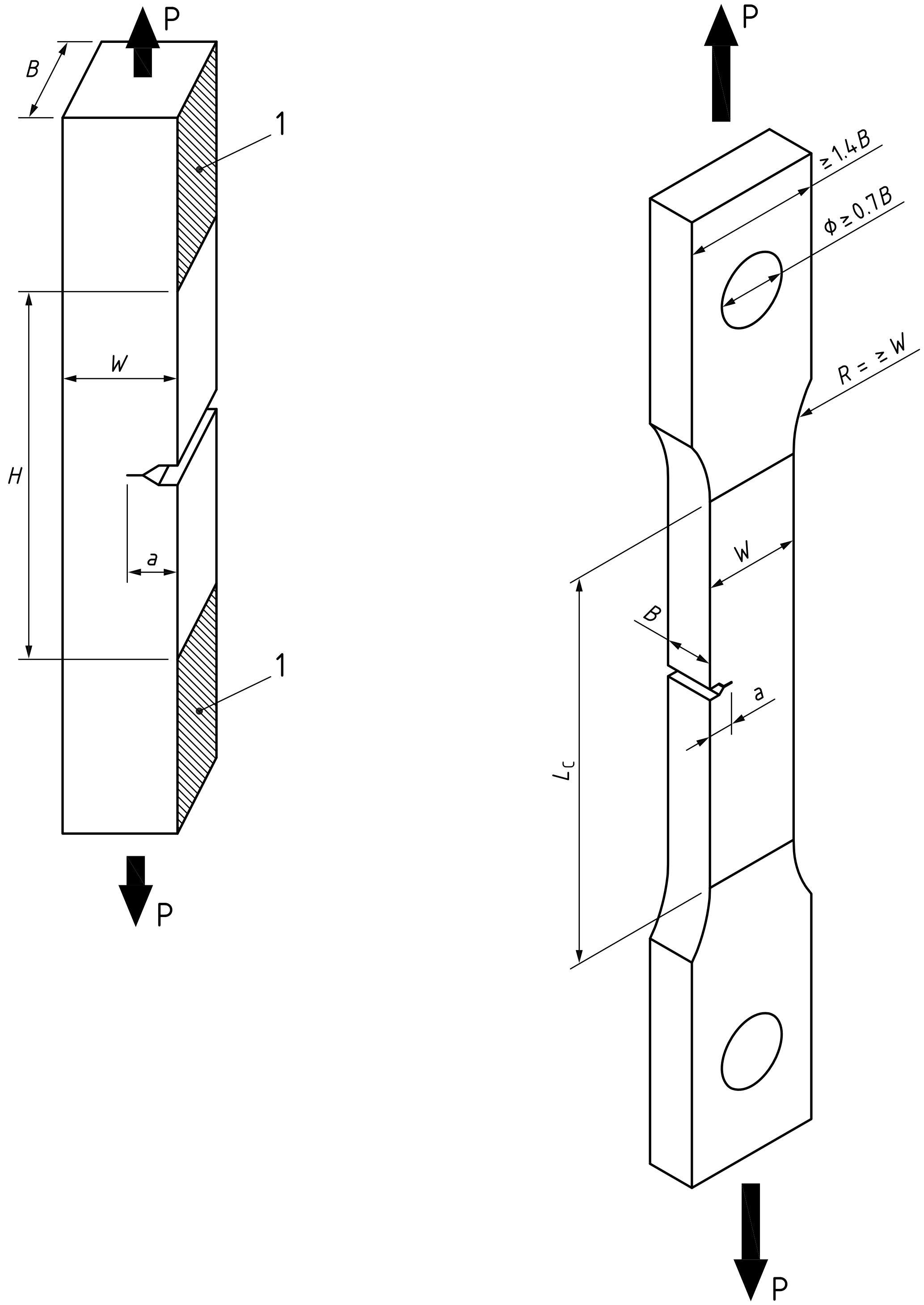


Figure 2 **SENT test specimen configuration**



a) Clamped single edge notched tension specimen

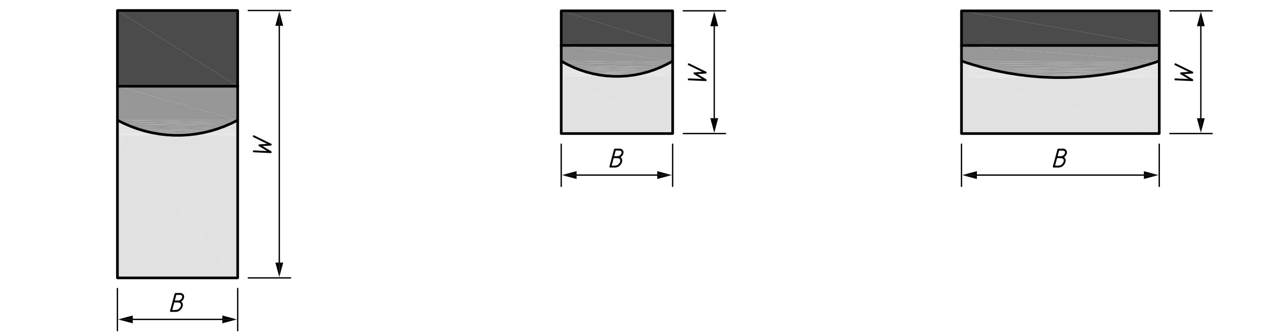
b) Directly pin-loaded single edge notched tension specimen

Key

1 Region of the specimen within the clamps

H Length between the grips

Figure 3 ***W/B* ratios in SENT test specimens**



a) *W*/*B*=2 b) *W*/*B*=1 c) *W*/*B*=0.5

Key

- Machined notch
- Fatigue pre-crack
- Ligament

NOTE Specimen type a) is suitable for through-thickness (NP) notching; b) can be used for surface (NQ) or through-thickness (NP) notching; c) is intended for surface notching (NQ). Crack plane orientations for fracture toughness specimens are given in Figure 5.

NOTE 1 For pin-loaded specimens J and CTOD equations are only provided for specimens with W/B ratios between 0.5 and 1.

The smaller dimension of the test specimen after machining shall be as close as possible to the full thickness of the source material. When preparing specimens from pipe sections, the machining along the specimen length shall be the minimum necessary to remove pipe curvature so that a square or rectangular cross-section is obtained.

NOTE 2 The test specimen thickness should be at least 85% of the thickness of the source material for pipeline applications.

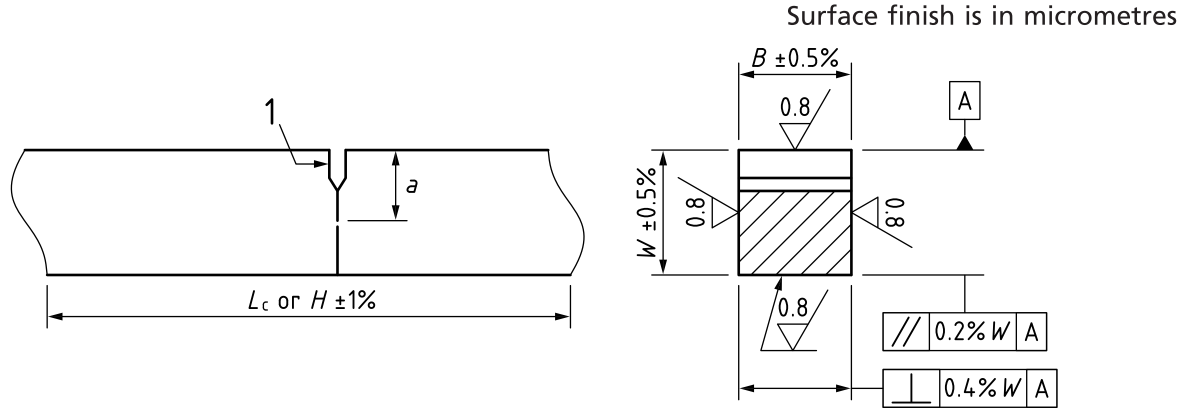
NOTE 3 The pin-loaded ends of the specimens should be sufficiently large to avoid the specimen yielding at the sides of the pin-holes. It might not be necessary for the gripped portions to be the same width or for them to be fully machined in the same way as the portion between the grips. The surface finish of the gripped region can be rougher than the central portion of the specimen, to aid gripping.

Testing of sub-size specimens where the specimen thickness is less than 85% of the material wall thickness shall be permitted. However, in such cases the original thickness and final specimen dimensions and position through thickness shall be given in the test report.

If samples cut from welds are not straight along their length because of distortions arising from the welding process (due to misalignment and/or angular distortion at the weld), distortions shall be removed by machining to obtain a straight specimen, noting restrictions regarding specimen thickness.

The portions of the reduced section on a test specimen and/or the section between the grips shall be fully machined within the tolerances, and with a surface finish as given in Figure 4.

Figure 4 **Machining tolerances and surface finish for a SENT specimen**



Key

1 Machined notch

a Crack length, including machined notch and fatigue pre-crack

For clamped test specimens tested between rigid grips, the distance, *H*, shall be 10 times the test specimen width, *W.*

The total length of the SENT specimen shall allow sufficient material to be within the grips for effective clamping.

NOTE 4 A length of 100 mm within each grip is usually sufficient for clamped specimens, although this depends on size of specimen, test machine, etc.

For pin-loaded specimens an increase in the clamping distance does not influence the results. Pin-loading means that there is no restraining bending moment from the testing machine on the SENT specimens in the plane of the fatigue crack. The specimen geometry as shown in Figure 2b) restricts its use to notch orientations of YX and XY for parent metals, and NP and PN for welds (see Figure 5 and **5.3**). The parallel length (L_c) of a pin-loaded specimen shall have a minimum length given by $L_c = 5.65\sqrt{(B \times W)}$.

*NOTE 5 Due to material restrictions it might be difficult, in practice, to obtain ideal pin-loading. However, the expressions in **7.4.3** are acceptable (if slightly conservative) if the specimen is gripped; e.g. in test machine wedge grips, or by other pin clevises connected to the testing machine with a bolt (pin) bearing. In this situation there is no restriction on the notch orientation.*

NOTE 6 For both test specimen configurations it is permissible to weld extension pieces to the specimen, for example, using electron beam welding or friction welding, to produce sufficient length provided the distance between the welds, and the associated HAZs, and the notched tip is at least equal to the test specimen width, W.

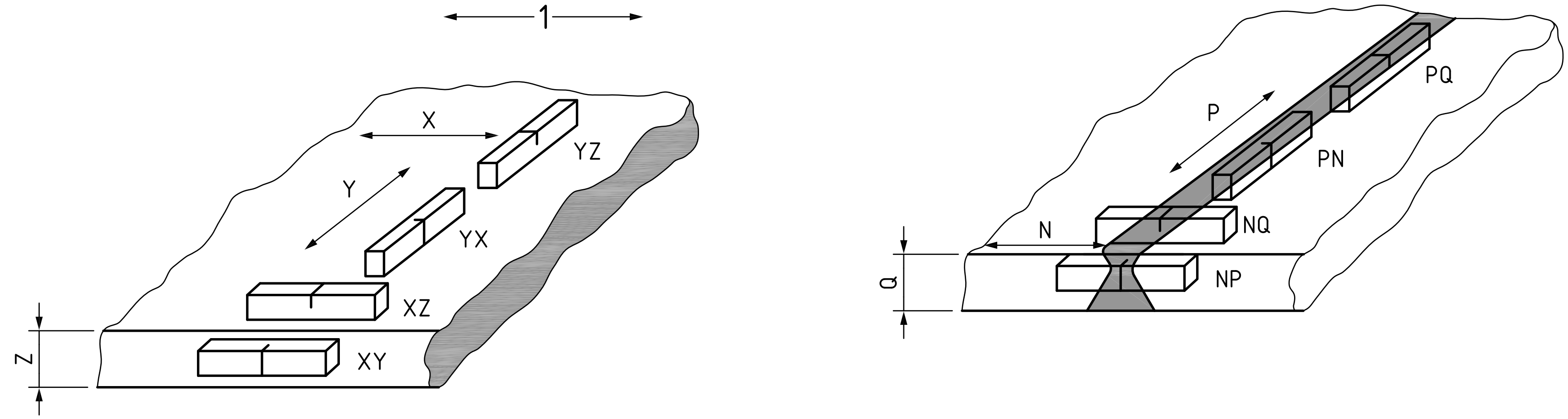
5.3 Notching

Specimens shall be notched from the surface specified by the customer. The specimen and crack plane orientation relative to the weld direction and the parent metal rolling direction shall be as given in Figure 5.

NOTE 1 The orientation of the notch determines which dimension is taken to be the thickness, B, and which is taken to be the width, W.

NOTE 2 W is the same direction as the notch (so that the crack depth may be expressed as the a/W ratio) and B is the dimension perpendicular to this.

Figure 5 **Crack plane orientation code for fracture toughness specimens of parent metal and weld metal**



a) Parent metal

b) Weld metal

Key

1 Primary working/rolling direction
N Normal to weld direction
■ Weld metal
P Parallel to weld direction
Q Weld thickness direction

First letter designation: the normal to the crack plane.

Second letter designation: the expected direction of crack propagation.

Specimen orientations NQ and PQ are surface notched.

Where the notch is to be located into the weld or HAZ, pre-test metallography shall be used to correctly position the notch.

NOTE 3 Guidance on pre-test metallography and location of the notch and fatigue pre-crack is given in BS EN ISO 15653.

When marking the placement of a notch, reference lines shall be scribed upwards on both sides of the specimen from the intended notch tip location, and then perpendicular lines shall be scribed on the surface from each side reference line. The actual line used to delineate the intended plane of the machined notch shall be marked on the surface equidistant between these two lines.

The notching shall be carried out using standard machining or electro-discharge machining (EDM) such that the notch width at the notch tip is no wider than $W/16$. The final crack depth (after fatigue pre-cracking), given as the ratio of crack depth, a, to specimen width, W, shall be in the range $0.2 \leq a/W \leq 0.5$.

NOTE 4 There is a minimum notch depth needed to avoid yielding in the arms of an overmatched weld SENT specimen which otherwise might restrict the amount of crack extension during the test, and limit the R-curve that can be generated. For a weld with an overmatch ratio, M (equal to the weld metal yield strength divided by the parent metal yield strength or $R_{p0.2w}/R_{p0.2b}$*), the minimum a/W ratio is given by the following equation:*

$$\frac{a}{W} = -0.107M^2 + 0.536M - 0.261 \quad (1)$$

5.4 Fatigue pre-cracking

Fatigue pre-cracking shall be carried out in bending in accordance with ISO 12135 for parent metal specimens and in accordance with BS EN ISO 15653 for weld or HAZ specimens. The minimum length of the fatigue pre-crack shall be the larger of 1.3 mm or 2.5% W, as given in ISO 12135.

NOTE 1 When fatigue pre-cracking through-thickness (NP, see Figure 5) notches in weld and HAZ specimens it can be difficult to obtain sufficiently straight fatigue pre-crack shapes due to the residual stresses present. Guidance on methods for fatigue pre-cracking welded specimens is given in BS EN ISO 15653:2010, Annex C.

NOTE 2 Side grooving is a technique which can improve the straightness of stable tearing front during R-curve testing. There is insufficient research on SENTs to confirm that this method is necessary for all test methods. If side grooving is going to be used for SENT specimens, a groove depth of 5% of the specimen thickness on each side is recommended. The side groove angle and root radius should be in accordance with ISO 12135.

6 Test procedure

6.1 Measurements during testing

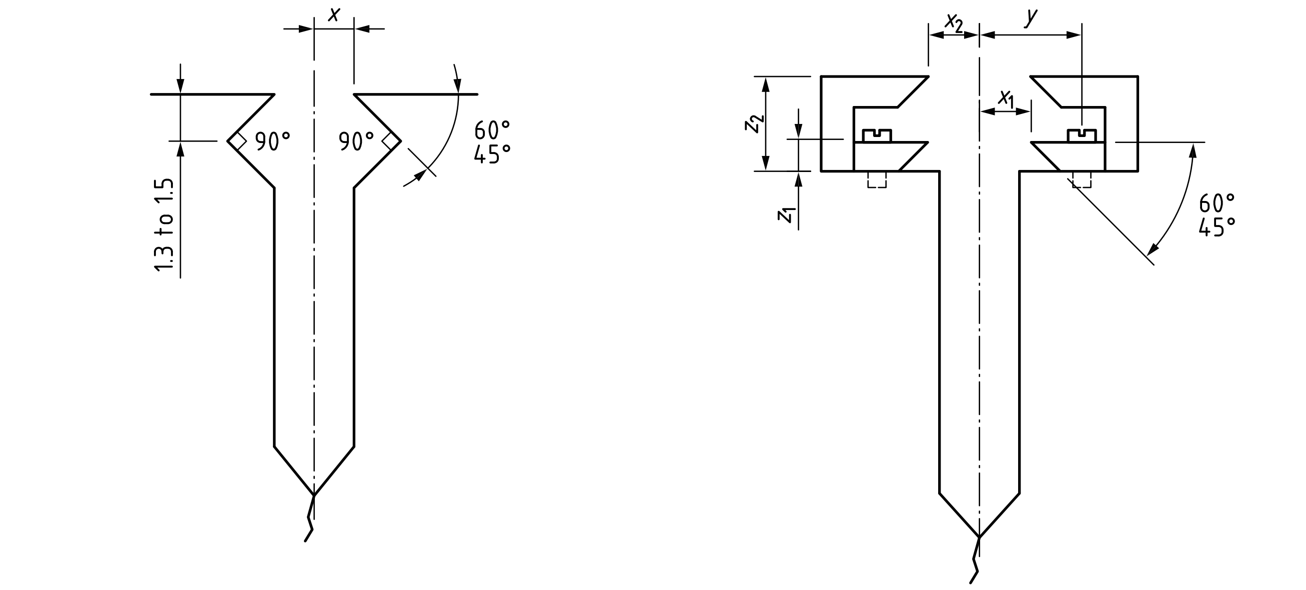
Tests shall be carried out under crosshead-displacement control and the crack opening measured using clip gauges.

Either integral knife edges shall be machined into the specimen or a pair of knife edges attached on each side of the notch close to the notch mouth, at two different heights above the crack mouth, or a combination of both, shall be used. A pair of clip gauges (double-clip) shall be used to measure the crack opening at these knife edge positions; examples of this are shown in Figure 6.

NOTE 1 Using a double clip gauge arrangement allows both CTOD and J to be determined.

NOTE 2 Using integral knife edges and a single clip gauge can obtain J-integral only.

Figure 6 **Example knife edges and notch geometries**



a) Integral knife edges

b) Attached double knife edges

Key

2*x* ≤*W*/2

2*y* + Screw thread diameter ≤*W*/2

6.2 Test specimen temperature

6.2.1 General

The test specimen temperature shall be as specified by the customer, and controlled and recorded to an accuracy of ±2 °C. For this purpose, a thermocouple or platinum resistance thermometer shall be placed in contact with the surface of the specimen no further than 5 mm from the crack tip.

Tests shall be made in situ in a suitable high, ambient or low temperature medium, in accordance with **6.2.2** and **6.2.3**, as applicable.

6.2.2 Testing in a liquid medium

Before testing in a liquid medium, the specimen shall be retained in the liquid for a soaking time of 30 s/mm of thickness, *B*, after the surface of the specimen has reached the required temperature.

6.2.3 Testing in a gaseous medium

When testing in a gaseous medium, the specimen shall be retained in the medium for a soaking time of at least 60 s/mm of thickness, *B*, after the surface of the specimen has reached the required temperature. The minimum soaking time at the test temperature shall be 15 min. The temperature of the test specimen shall be maintained within 2 °C of the nominal test temperature throughout the test and shall be recorded in the test report.

NOTE Care should be taken when testing at low temperatures without a test chamber to keep the grips at a similar temperature to that close to the crack tip, to avoid the specimen yielding away from the crack (see ***6.2.1****).*

6.2.4 Testing using heating/cooling

When using heating or cooling pads, the soaking time shall be 30 s/mm of thickness, *B*, after the surface of the specimen has reached the required temperature within 5 mm of the notch.

6.3 Testing rate

The load-line displacement rate shall be such that within the linear elastic region, the stress intensity rate is within the range 0.2 $MPa \cdot m^{0.5} \cdot s^{-1}$ and 3 $MPa \cdot m^{0.5} \cdot s^{-1}$. For each series of tests, all specimens shall be loaded at the same nominal rate.

6.4 Post-test measurements

The specimen shall be broken open after testing and its fracture surface examined to determine the original crack length, a_0, and any stable crack extension, Δa, that might have occurred during the test.

The initial crack length, a_0, shall be measured to the tip of the fatigue crack, based on nine measurements made across the crack front in accordance with ISO 12135. The total crack extension including any crack blunting, Δa, between the initial and final crack fronts shall also be determined in accordance with ISO 12135. Measurements shall be made in the same plane as the notch, even if tearing has occurred out-of-plane.

NOTE 1 For some tests it might be necessary to mark the extent of stable crack extension before breaking open the specimen. Stable crack extension may be marked by heat tinting or by post-test fatiguing. Care should be taken to minimize post-test specimen deformation. Cooling ferritic steels can help ensure brittle behaviour during specimen opening.

NOTE 2 If there is reason to believe that the fracture face on each side of the SENT test specimen shows different levels of tearing, the one showing larger tearing should be used to determine the R-curve.

7 Determination of resistance curves δ–Δa and J–Δa

7.1 General

Resistance curves (R-curves) shall be generated using either multiple specimen or single specimen methods. If a single specimen method is used to generate an R-curve, it shall be validated against a multiple specimen method.

NOTE Different material types might require separate validation.

7.2 Multiple specimen method

When using the multiple specimen method to produce an R-curve, the results from a minimum of six specimens which gave valid results (based on the requirements given in **9.1**) shall be used for each R-curve.

Tests shall be performed at a range of crack extensions from 0.2 mm of crack extension up to a maximum of 20% of the specimen ligament (W-a_o).

The results for each specimen shall be used to provide one point on the CTOD or J R-curve. For each test specimen, the value of J and/or CTOD shall be determined in accordance with **7.4** and/or **7.5** at the point of unloading.

7.3 Single specimen methods

At least three identical specimens shall be tested using the same technique.

NOTE 1 Possible single specimen methods include unloading-compliance and direct current potential drop (DCPD) methods.

NOTE 2 Unloading compliance methods for SENT specimens are given in Cravero and Ruggieri [1] and Shen, Gianetto and Tyson [2]. An example of the use of DCPD is given by Verstraete et al [3].

7.4 Calculating *J*

7.4.1 General

J shall be calculated at the unloading point using the following equation:

$$J = J_{el} + J_{pl} = \frac{K^2}{E'} + \frac{\eta_p U_p}{B(W - a_0)} \qquad (2)$$

where:

J_{el} is the elastic component of *J*, in kilojoules per metre squared or newtons per millimetre (kJ/m² or N/mm);

J_{pl} is the plastic component of *J*, in kilojoules per metre squared or newtons per millimetre (kJ/m² or N/mm);

E′ is the longitudinal elastic modulus in plane strain, equal to $E/(1-\nu^2)$, in newtons per millimetre squared (N/mm²);

η_p is a dimensionless function of geometry;

U_p is the area under the plastic part of the load versus CMOD curve, in newton millimetres (N·mm) (see Figure 7);

B is the specimen thickness, perpendicular to the width, in millimetres (mm). When side-grooved specimens are used, the value of thickness to use in equation (2) is $\sqrt{(B \times B_N)}$, where *B* is the thickness before side-grooving and B_N is the net section thickness after side-grooving;

W is the specimen width, measured in the direction of the notch, in millimetres (mm);

a_0 is the initial crack length (comprising the machined notch and fatigue pre-crack length), in millimetres (mm);

$(W - a_0)$ is the specimen ligament;

K is calculated in accordance with **7.4.2** *for clamp-loaded specimens and* ***7.4.3*** *for pin-loaded specimens; and*

CMOD is given by the following equation when using a double clip gauge:

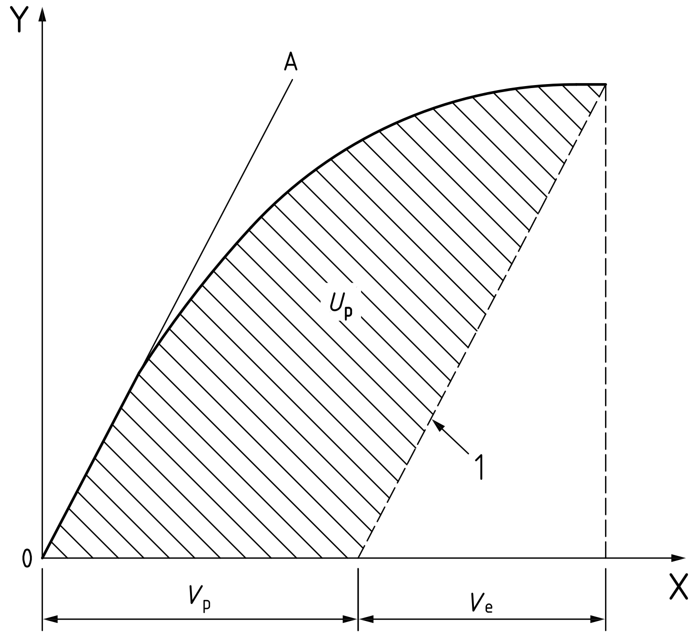
$$V_0 = V_{p1} - \frac{z_1}{z_2 - z_1}(V_{p2} - V_{p1}) \qquad (3)$$

where:

V_{p1} and V_{p2} are the plastic parts of the clip gauge displacements for knife heights of z_1 and z_2, respectively, as shown in Figure 6b).

NOTE This equation for J is taken from DNV RP F108 [4] and is valid for specimens with W/B ratios between 0.5 and 1 [as shown in Figures 3b) and 3c)].

Figure 7 **Determination of U_p, V_p and V_e**



Key

X Crack mouth opening displacement, V_0

Y Applied force

1 Line parallel to the elastic part of the load-displacement trace (line 0A), offset to intersect at the point of assessment

7.4.2 Clamped specimens

K for clamped specimens shall be calculated using the following equation:

$$K = \frac{P}{(B \times B_N)^{0.5} W} \sqrt{\pi a_0} (f_1 - 6 \xi_3 f_2) \quad (4)$$

where:

P = force

$$\xi_3 = \frac{\xi_1}{\xi_2 + 12\frac{H}{W}} \quad (5)$$

$$\xi_1 = 12\pi \left(\frac{a_0}{W}\right)^2 \sum_{i=0}^{8} q_i \left(-\frac{a_0}{W}\right)^i - U_+\left(\frac{a_0}{W} - 0.6\right) \times \left[19.95 - \frac{3.99(3a_0/W - 1)}{(1 - a_0/W)^2}\right] \quad (6)$$

$$\xi_2 = 72\pi \left(\frac{a_0}{W}\right)^2 \sum_{i=0}^{8} r_i \left(-\frac{a_0}{W}\right)^i - U_+\left(\frac{a_0}{W} - 0.6\right) \times \left[99.38 - \frac{15.9}{(1 - a_0/W)^2}\right] \quad (7)$$

$$f_1 = U_-\left(0.6 - \frac{a_0}{W}\right) \times \sum_{i=0}^{4} n_i \left(-\frac{a_0}{W}\right)^i + U_+$$

$$\left(\frac{a_0}{W} - 0.6\right) \times \frac{(1 + 3a_0/W)}{3.545(a_0/W)^{0.5}(1 - a_0/W)^{1.5}} \quad (8)$$

$$f_2 = U_-\left(0.6 - \frac{a_0}{W}\right) \times \sum_{i=0}^{4} \mathrm{m_i}\left(-\frac{a_0}{W}\right)^i + U_+$$
$$\left(\frac{a_0}{W} - 0.6\right) \times \frac{0.375}{(a_0/W)^{0.5}(1 - a_0/W)^{1.5}} \quad (9)$$

U_+ and U_- are Heaviside functions with the values given below:

$U_+(x) = 0$ for $x \leq 0$

$U_+(x) = 1$ for $x > 0$

$U_-(x) = 0$ for $x < 0$

$U_-(x) = 1$ for $x \geq 0$

The constants $\mathrm{n_i}$, $\mathrm{m_i}$, $\mathrm{q_i}$ and $\mathrm{r_i}$ for iterative values of *i* are as given in Table 1.

Table 1 **Values of constants $\mathbf{n_i}$, $\mathbf{m_i}$, $\mathbf{q_i}$ and $\mathbf{r_i}$**

i	$\mathrm{n_i}$	$\mathrm{m_i}$	$\mathrm{q_i}$	$\mathrm{r_i}$
0	1.120	1.122	0.629	0.629
1	0.231	1.400	0.609	1.047
2	10.550	7.330	5.093	4.602
3	21.720	13.080	11.097	9.975
4	30.390	14.000	26.757	20.295
5	—	—	48.997	32.993
6	—	—	81.820	47.041
7	—	—	77.953	40.693
8	—	—	42.456	19.600

η_p shall be calculated from the following equation:

Equation (10):

$$\eta_\mathrm{p} = 0.85 \times \left[\begin{array}{l} \left\{196.719e^{-\left(\frac{B}{W}\right)} - 64.642\right\}\left(\frac{a_0}{W}\right)^5 + \left\{-493.511e^{-\left(\frac{B}{W}\right)} + 138.837\right\}\left(\frac{a_0}{W}\right)^4 + \\ \left\{463.503e^{-\left(\frac{B}{W}\right)} - 106.207\right\}\left(\frac{a_0}{W}\right)^3 + \left\{-201.862e^{-\left(\frac{B}{W}\right)} + 34.532\right\}\left(\frac{a_0}{W}\right)^2 + \\ \left\{39.413e^{-\left(\frac{B}{W}\right)} - 4.525\right\}\frac{a_0}{W} + \left\{-2.064e^{-\left(\frac{B}{W}\right)} + 1.039\right\} \end{array}\right]$$

This shall be used for $0.2 \leq a_0/W \leq 0.5$ and $0.5 \leq W/B \leq 1$ and $\mathrm{H} = 10W$.

NOTE 1 Equations (2) to (10) are taken from DNV RP F108 [4] and are not validated for SENT specimens with W/B ratio >1 (such as shown in Figure 3a), and so alternative J equations are used in this case. These are based on the equation for J, from work by Shen et al (2009) [2], but simplified for a single crack length rather than a growing crack.

J for *W/B* = 2 shall be calculated as follows:

$$J = \frac{K^2(1 - \nu^2)}{E} + J_\mathrm{pl} \quad (11)$$

and:

$$J_{pl} = \left(\frac{\eta_{CMOD}}{W - a}\right)\left(\frac{Up}{B_N}\right) \qquad (12)$$

$$K = \left[\frac{P\sqrt{\pi a}}{(B \times B_N)^{1/2} W}\right] G\left(\frac{a}{W}\right) \qquad (13)$$

where:

$$G\left(\frac{a}{W}\right) = \sum_{i=1}^{12} t_i \left(\frac{a}{W}\right)^{i-1} \qquad (14)$$

t_i for *H*/*W*=10 are as follows and valid for 0.05 ≤ *a*/W ≤ 0.95:

i	t_i
1	1.197
2	–2.133
3	23.886
4	–69.051
5	100.462
6	–41.397
7	–36.137
8	51.215
9	–6.607
10	–52.322
11	18.574
12	19.465

$$\eta_{CMOD} = \sum_{i=0}^{10} \varphi_i (a/W)^i \qquad (15)$$

φ_i for *H*/*W*=10 are as follows and are valid for 0.05 ≤ *a*/*W* ≤ 0.7:

i	φ_i
0	1.000
1	–1.089
2	9.519
3	–48.572
4	109.225
5	–73.116
6	–77.984
7	38.487
8	101.401
9	43.306
10	–110.770

a is the crack size, in millimetres (mm);

a_0 is the original crack size, in millimetres (mm);

U_p is the plastic area under the load versus CMOD curve;

B is specimen thickness, in millimetres (mm);

B_N is net specimen thickness, in millimetres (mm);

P is the load, in newtons (N);

W is the specimen width, in millimetres (mm).

NOTE 2 This method to determine J gives less than 10% difference compared to the method taken from DNV RP F108 [4] for single values of fracture toughness from equivalent specimens.

7.4.3 Pin-loaded specimens

For pin-loaded specimens *J* shall be calculated using equation (2), along with the following formulae. *K* for pin-loaded specimens shall be calculated from the following equation:

$$K = F\left(\frac{a_0}{W}\right) \times \sigma\sqrt{\pi a_0} \qquad (16)$$

where:

σ is the nominal stress on the specimen and $F(a/W)$ is a geometric factor given by the following equation:

$$F\left(\frac{a}{W}\right) = 1.12 - 0.231\left(\frac{a_0}{W}\right) + 10.55\left(\frac{a_0}{W}\right)^2 - 21.72\left(\frac{a_0}{W}\right)^3 + 30.39\left(\frac{a_0}{W}\right)^4 \qquad (17)$$

η_p is calculated from the following equation:

Equation *(18)*:

$$\eta_p = 0.88 \times \left[\left\{209.747e^{-\left(\frac{B}{W}\right)} - 85.668\right\}\left(\frac{a}{W}\right)^5 + \left\{-467.666e^{-\left(\frac{B}{W}\right)} + 195.032\right\}\left(\frac{a}{W}\right)^4 + \left\{393.925e^{-\left(\frac{B}{W}\right)} - 163.572\right\}\left(\frac{a}{W}\right)^3 + \left\{-160.931e^{-\left(\frac{B}{W}\right)} + 61.334\right\}\left(\frac{a}{W}\right)^2 + \left\{32.319e^{-\left(\frac{B}{W}\right)} - 9.568\right\}\frac{a}{W} + \left\{-1.72e^{-\left(\frac{B}{W}\right)} + 1.333\right\} \right]$$

This shall be used for $0.2 \le a_0/W \le 0.5$ and $0.5 \le W/B \le 1$.

7.5 Calculating CTOD

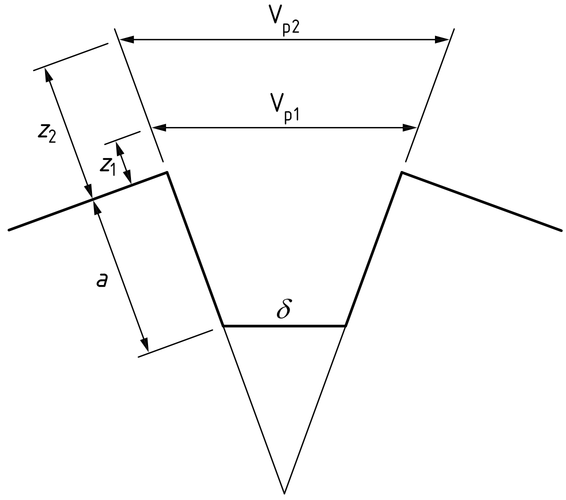
CTOD shall be calculated at the unloading point from the double clip gauge measurements as shown in Figure 8. The clip gauge displacement shall be divided into its elastic and plastic components. CTOD shall be determined using the following equation:

$$\delta = \frac{\left(1-u^2\right)K_I^2}{2R_{p0.2}E} + v_{p1} - \frac{a_0+z_1}{z_2-z_1}\left(V_{p2}-V_{p1}\right) \quad (19)$$

The elastic component of CTOD shall be calculated from the elastic stress intensity factor, K_I, at unloading, as given in **7.4.2** and **7.4.3**. V_{p1} and V_{p2} are the plastic parts of the clip gauge displacements for knife heights of z_1 and z_2 respectively. The value of $R_{p0.2}$ shall be $R_{p0.2b}$ if the crack is located in parent metal or $R_{p0.2w}$ if the crack is located in weld metal or HAZ.

V_{p1} and V_{p2} are the plastic components of the clip gauges 1 and 2 of double clip, calculated as shown in Figure 8.

Figure 8 **Determination of CTOD (δ) from the double clip gauge arrangement**



NOTE The double clip method allows the crack mouth opening displacement, and the crack tip opening displacement to be determined using the principle of similar triangles with their apex at a given point of rotation of the specimen.

7.6 Definition of the R-curve

The data shall be plotted as fracture toughness (CTOD or *J*) against the stable crack extension, Δa. The CTOD or *J* R-curve line shall be fitted to the test data, either as a best-fit curve, or as a lower-bound, as required for the application. The R-curve equation shall be of the form:

$$J \text{ (or CTOD)} = m + l\,(\Delta a)^x \quad (20)$$

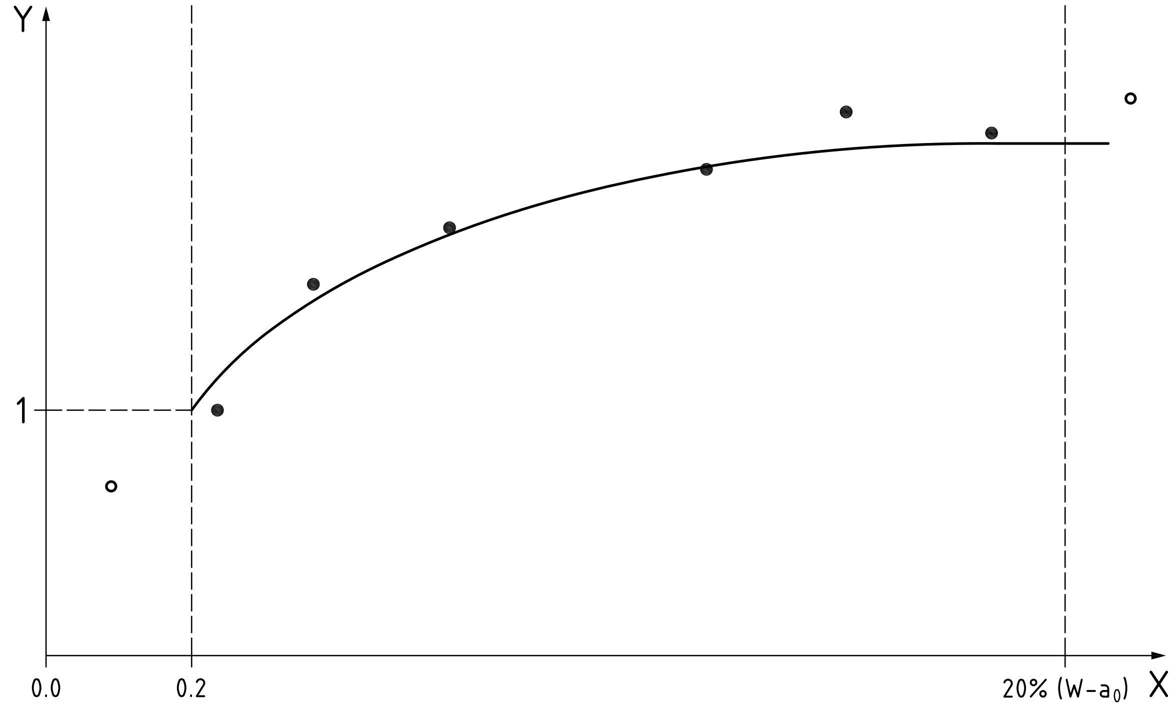
where m, l and x are constants with $l \geq 0$ and $0 \leq x \leq 1$, and m is the intercept on the Y axis and might be 0.

The R-curve shall be fitted to crack extensions between 0.2 mm and the maximum crack extension from the test data, or 20% of the specimen ligament (W-a_o) (whichever is smaller). When the multiple specimen method is used, the R-curve shall be fitted to a minimum of six qualified results within this range.

NOTE No blunting line is necessary when fitting the data.

If a value of initiation fracture toughness is required, it shall be defined as the value of *J* or CTOD at 0.2 mm of crack extension from the R-curve fit, as shown in Figure 9.

Figure 9 **Fitting the R-curve to the SENT crack extension data**



Key

—— Fitted R-curve, extrapolated to 0.2 mm crack extension to determine $J_{0.2}$ or $\delta_{0.2}$

1 Initiation value of fracture toughness, $J_{0.2}$ or $\delta_{0.2}$

○ Data with Δa < 0.2 mm: excluded from curve fit but plotted

● Data used in fitting the R-curve

7.7 Assessment of pop-ins

Any pop-ins during testing shall be assessed in accordance with BS EN ISO 15653:2010, Annex D. Test specimens which give significant pop-in results shall not be used to generate R-curves, therefore the R-curve can be generated only up to the first pop-in.

8 Determination of single point fracture toughness

The values of *J* and/or CTOD shall be determined using the equations given in **7.4** and **7.5** using the load and displacement measurements taken at the point of fracture, significant pop-in, or at the maximum force plateau, whichever occurred first during the test. Single point values of fracture toughness shall be reported in terms consistent with ISO 12135 for parent metal specimens and with BS EN ISO 15653 for weld and HAZ specimens.

NOTE There has been little research published on the application of SENT tests for brittle materials and caution should be applied when using "brittle" single point test results in fitness-for-service assessment of pipelines, especially where shallow notched specimens with a/W < 0.4 have been used.

9 Test data qualification

9.1 Checklist for qualification

All of the qualification checks listed in ISO 12135:2002, **8.3.6** shall be used (together with those listed in BS EN ISO 15653:2010, **12.4** when testing weld specimens), with the following modifications.

a) The specimen shall conform to the dimensions and tolerances given in Clause **5**.

b) The average initial crack length, a_0, shall be within the range $0.2W$ to $0.5W$.

c) None of the nine initial crack length measurements shall differ from the average a_0 by more than $0.2a_0$.

NOTE The data for this are taken from Malpas, Moore and Pisarski [5].

d) No two of the nine measurements of stable crack extension, Δa, shall differ by more than 20% of the mean Δa or 0.15 mm, whichever is greater.

9.2 Test report

The test report shall be in accordance with ISO 12135, except that the distance between the grips, H, for clamped specimens, and gauge length, L_c for pin-loaded specimens, shall be reported instead of the loading span. For weld and HAZ notched specimens, the additional test report requirements of BS EN ISO 15653 shall be included.

Annex A (informative) Example calculation of *J* for SENTs

A clamped SENT specimen which has a thickness of 40 mm, a width of 20 mm, and has a 7 mm deep notch and is loaded to a maximum force of 300 kN gives a plastic area under the force versus CMOD curve of 800 kN·mm. The specimen is made from steel with a modulus of elasticity of 207 000 N/mm². *J* is determined in the following way:

B = 40 mm

W = 20 mm

a_0 = 7 mm

U_p = 800 000 N/mm

P = 300 000 N

Assume H = 10W = 200 mm

Assume E' = E/(1-ν²) = 207 000/1–0.3² = 227 472.5 N/mm²

a_0/W = 0.35

B/W = 2

Using the equations in **7.4**:

$$J = J_{el} + J_{pl} = \frac{K^2}{E'} + \frac{\eta_p U_p}{B(W - a_0)}$$

start by working out the value of K for clamped specimens using the equations and Table 1 in **7.4.2**.

$$K = \frac{P}{(B \times B_N)^{0.5} W}\sqrt{\pi a_0}(f_1 - 6\xi_3 f_2)$$

The Heaviside functions:

$$U_-(0.6 - a_0 / W) = 1$$

$$U_+(a_0 / W - 0.6) = 0$$

From equation (6) ξ_1 is 3.777.

From equation (7) ξ_2 is 16.475.

From equation (5) ξ_3 is therefore 0.0277.

From equation (8) f_1 is 1.856.

From equation (9) f_2 is 1.179.

Therefore K = 2 920 N/mm$^{1.5}$

The value of J_{el} is calculated to be K^2/E' = 37.48 N/mm

To determine J_{pl} the value of η_p has to be calculated from equation (10), which gives a value of 0.802.

J_{pl} is therefore 1 234.1 N/mm.

The value of J for this specimen equals J_{el} + J_{pl} = 37.48 + 1234.1 = 1 272 N/mm.

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