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Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds

Matériaux métalliques — Méthode d'essai pour la détermination de la ténacité quasi statique à la rupture des soudures

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 15653 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T).*

Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds

1 Scope

This International Standard specifies methods for determining fracture toughness in terms of K (stress intensity factor), δ (crack tip opening displacement, CTOD) and J (experimental equivalent of the J-integral) for welds in metallic materials.

This International Standard is complementary to ISO 12135, which covers all aspects of fracture toughness testing of parent metal and which needs to be used in conjunction with this document. This International Standard describes methods for determining point values of fracture toughness. It should not be considered a way of obtaining a valid R-curve (resistance-to-crack-extension curve). However, the specimen preparation methods described in this International Standard could be usefully employed when determining R-curves for welds. The methods use fatigue precracked specimens which have been notched, after welding, in a specific target area in the weld. 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 within the weld heat-affected zone (HAZ), and then, where appropriate, to evaluate the effectiveness of the fatigue crack in sampling these areas.

2 Normative references

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

ISO 3785, *Metallic materials — Designation of test specimen axes in relation to product texture*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12135 and the following apply.

3.1
stretch zone width
SZW
increase in crack length associated with crack tip blunting — i.e. prior to the onset of unstable crack extension, pop-in (see 3.3) or slow stable crack extension — and occurring in the same plane as the fatigue precrack

3.2
target area
intended fatigue crack tip position within the weld metal or HAZ

NOTE See 3.7 and 3.9.

3.3
pop-in
an abrupt discontinuity in the force versus displacement record, featured as a sudden increase in displacement and, generally, a sudden decrease in force, subsequent to which displacement and force increase to above their values at pop-in

3.4
local compression
controlled compression applied to specimens in the thickness direction on the unnotched ligament prior to fatigue cracking using hardened steel platens

NOTE See Annex C.

3.5
welding
an operation in which two or more parts are united by means of heat, friction, pressure or all three of these, in such a way that there is continuity in the nature of the metal between these parts

NOTE Filler metal, the melting temperature of which is of the same order as that of the parent metal, may or may not be used.

3.6
weld
union of pieces of metal made by welding

3.7
weld metal
all metal melted during the making of a weld and retained in the weld

3.8
parent metal
base metal
metal to be joined by welding

3.9
heat-affected zone
HAZ
zone in the parent metal that is metallurgically affected by the heat of welding

3.10
fusion line
FL
junction between the weld metal and the parent metal heat-affected zone

3.11
weld positional
WP
target position for the fatigue crack tip, defined with respect to a reference line

NOTE See Figure A.1 for examples.

3.12
specific microstructure
SM
target microstructure for the fatigue crack tip

NOTE See Figure A.2 for examples.

3.13
specimen blank
specimen prepared from weld metal plus parent metal prior to notching

3.14
postweld heat treatment
heat treatment applied after welding for the purpose of reducing residual stresses or modifying weld properties

4 Symbols and units

For the purposes of this document, the symbols and units given in Table 1 apply in addition to those in ISO 12135.

Table 1 — Symbols and units

Symbol	Unit	Designation
d_1, d_2	mm	Lengths of microstructural features associated with pop-in.
h	mm	Effective weld width, defined as shortest distance between fatigue crack tip and weld fusion line within the central 75 % of the thickness (see Figures 13 and 14).
HV10		Vickers hardness using 10 kg force.
N		Normal to welding direction.
P		Parallel to welding direction.
Q		Weld thickness direction.
$R_{p0,2b}$	MPa	0,2 % offset yield strength of parent metal at the temperature of the fracture test.
$R_{p0,2w}$	MPa	0,2 % offset yield strength of weld metal at the temperature of the fracture test.
R_{mb}	MPa	Tensile strength of parent metal at the temperature of the fracture test.
R_{mw}	MPa	Tensile strength of weld metal at the temperature of the fracture test.
s_1	mm	Distance between crack tip and target area measured in the crack plane (see Figure 12).
s_2	mm	Distance between crack tip and target area measured perpendicular to the crack plane (see Figure 12).
V, V_1, V_2	mm	Crack mouth opening displacement.
X		Direction parallel to primary grain flow of parent metal.
Y		Direction transverse to primary grain flow and to thickness of parent metal.
Z		Direction through thickness of parent metal.
Δa_{pop}	mm	Maximum length of brittle crack extension (beyond SZW) (see 3.1) associated with pop-in.
λ	mm	Length of specific microstructure measured in pre-test or post-test metallography (see Figure B.2).

5 Principle

This International Standard specifies procedures for the determination of fracture toughness on notched-plus-fatigue-cracked specimens taken from welds. It pertains to situations where the crack tip is

a) located in relation to a weld feature of interest, referred to as “weld positional” (WP);

b) specifically located within a microstructure of interest, referred to as “specific microstructure” (SM).

Metallographic examination of the weld is used to confirm that the target weld feature and/or microstructure is indeed present at the crack tip and in sufficient quantity for testing.

Specimen geometry and notch orientation are chosen, and a fatigue crack then extended from the specimen's notch tip into the target weld feature or microstructure by applying a controlled alternating force to the specimen. The purpose of the test is to determine weld fracture toughness in the absence of significant welding stresses. To achieve this and to produce a straight-fronted fatigue crack, modifications to the fatigue precracking procedure may be required. These modifications are usually necessary when testing as-welded or partially stress-relieved welds.

The fracture toughness test is performed and evaluated in accordance with ISO 12135, but subject to additional requirements of this test method regarding post-test analysis (see 12.1, 12.2 and 12.3) and qualification (see 12.4).

Post-test metallography is often required to make certain that the crack tip was located in the target weld feature and/or microstructure and to determine the significance of pop-ins.

The sequence of operations is summarized in Figure 1.

6 Choice of specimen design, specimen orientation and notch location

6.1 Classification of target area for notching

A specimen selected for weld positional (WP) testing is intended to test a defined weld region with respect to a reference position (e.g. the weld metal centreline).

A specimen selected for specific microstructure (SM) testing is intended to sample a specific microstructure along the whole or part of the crack front length within the central 75 % of the specimen thickness.

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

WP weld metal centreline notch locations sampling predominantly grain-refined regions may give misleading (overly high) values of fracture toughness for misaligned two-pass and parallel multi-pass welds. For these welds, it is recommended that the SM notch locations shown in Figures A.2 iv) and A.2 v), respectively, be used.

6.2 Specimen design

Specimen design shall be of compact or single-edge-notched bend configuration as defined in ISO 12135 and may be plain-sided or side-grooved. Bend specimens notched into the plate thickness (see Figures 2, 3 and 4, parent metal specimens XY and YX and weld metal specimens NP and PN) are referred to as through-thickness notched specimens, whilst those notched into the planar surface of the plate (see Figures 2, 3 and 4, parent metal specimens XZ and YZ and weld metal specimens NQ and PQ) are referred to as surface-notched specimens.

NOTE Tolerances on weld specimen dimensions are less stringent than those for testing parent metal (see 8.1).

Test specimens shall have the dimension B or W (see Figure 5) equal to the full thickness of the parent metal adjacent to the weld to be tested (excluding weld overfill).

Testing of sub-sized (i.e. B or $W <$ full thickness in directions Q for weld and Z for parent metal in Figures 2, 3 and 4) and/or side-grooved specimens is permitted, but shall be properly identified as such in the test report. Results from sub-sized and/or side-grooved specimens may differ from those from full-thickness specimens owing to size effects and/or different microstructural regions being tested.

6.3 Specimen and crack plane orientation

Specimen and crack plane orientation relative to the weld and parent metal working directions shall be defined using the identification system described in Figures 2, 3 and 4.

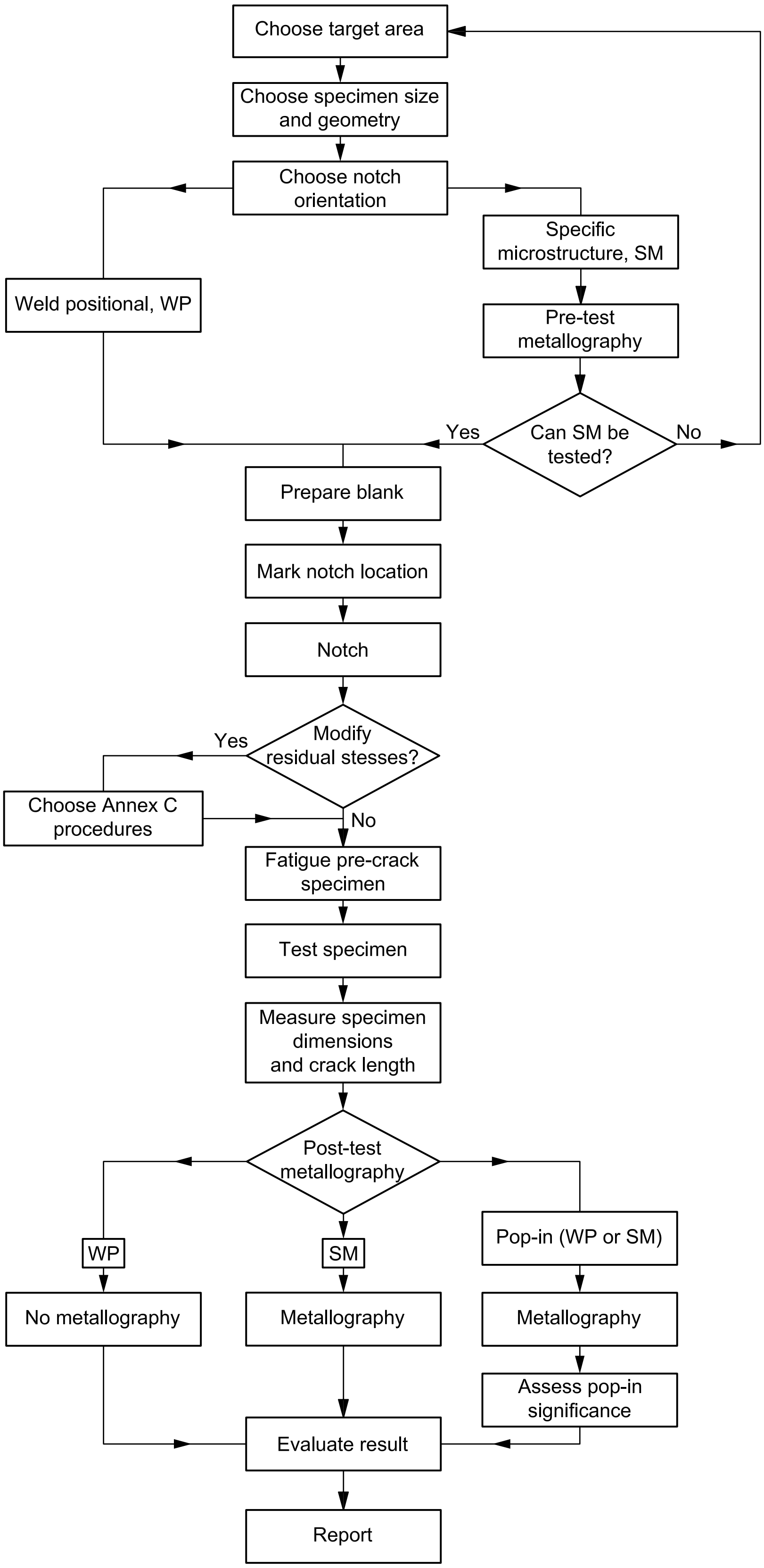
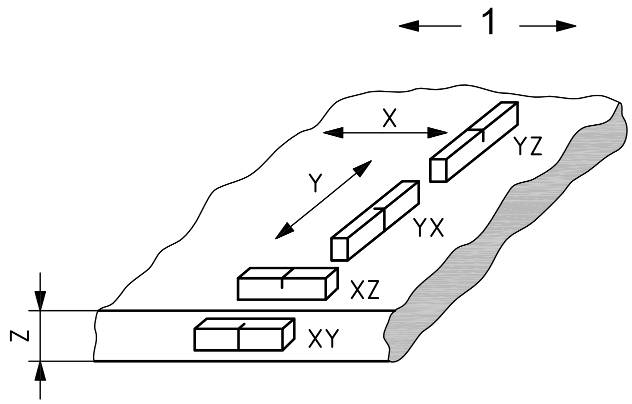
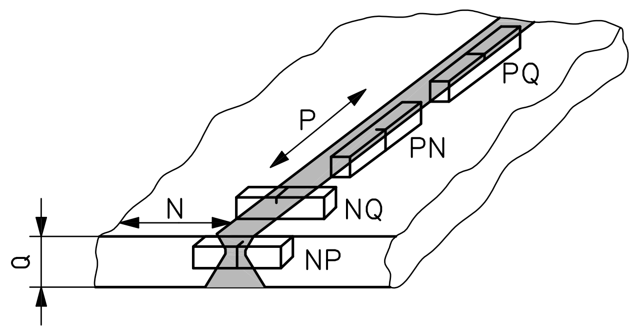


Figure 1 — Flow chart for testing



a) Parent metal



b) Weld metal

Key

1 rolling direction

N = normal to weld direction

P = parallel to weld direction

Q = weld thickness direction

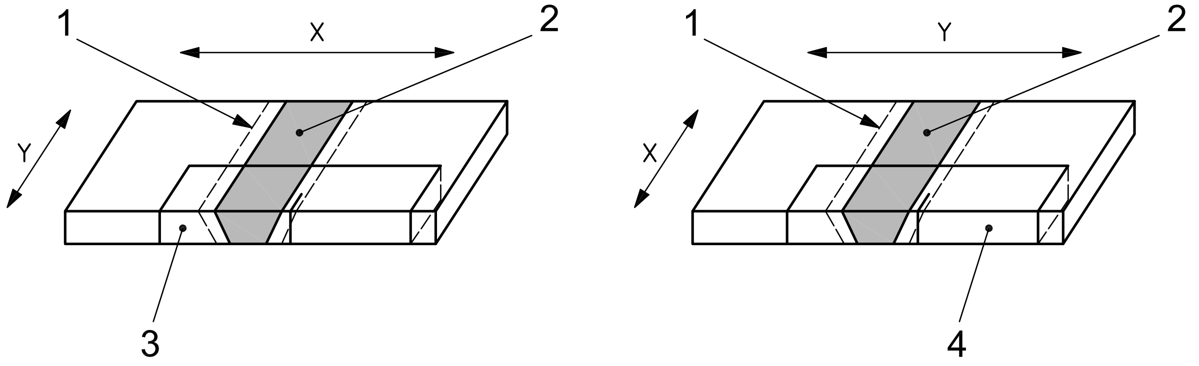
First letter in designation: the direction normal to the crack plane.

Second letter in designation: the expected direction of crack propagation.

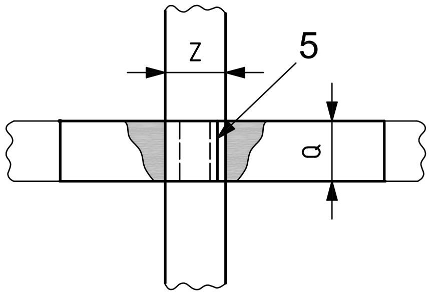
See ISO 3785 for the definitions of X, Y and Z.

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 fracture toughness specimens of parent metal and weld metal



a) Typical butt weld



b) Cruciform joint

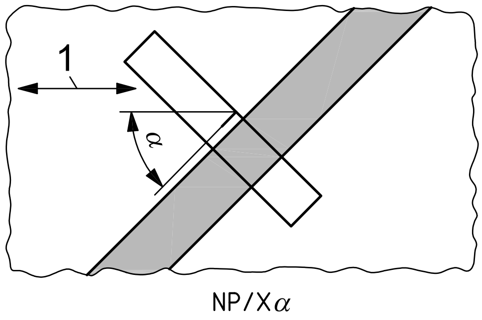
Key

1 HAZ
2 weld
3 weld specimen orientation NP/XY
4 weld specimen orientation NP/YX
5 through-crack NP/ZX or NP/ZY

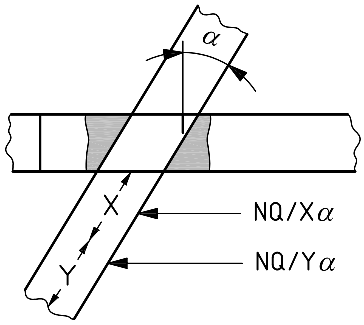
X = rolling direction
Q = weld thickness direction

For tests of the HAZ, where the rolling direction of the parent metal may affect resistance to crack extension, the weld and parent metal orientations may be combined to give both the weld direction and the parent metal rolling direction as shown in this figure and Figure 4.

Figure 3 — Crack plane orientation code for fracture toughness specimens for testing the HAZ of a typical butt weld and cruciform joint



a) Typical butt weld



b) Angled cruciform joint

Key

1 rolling direction

For tests of the HAZ, where the rolling direction of the parent metal may affect resistance to crack extension, the weld and parent metal orientations may be combined to give both the weld direction and the parent metal rolling direction as shown in this figure and Figure 3.

Figure 4 — Crack plane orientation code for fracture toughness specimens for testing the HAZ at an angle, α, to the parent metal rolling direction for a typical butt weld and angled cruciform joint

7 Pre-machining metallography

7.1 Microstructural assessment of macrosections

When the notch target area is defined as SM, either separate macrosections or the ends of the welds shall be prepared with the plane of the section perpendicular to the welding direction. These transverse weld sections shall bound the length of weld to be tested to ensure that the target microstructure is present at the expected crack tip position and in sufficient quantity for testing. The macrosections shall be polished, etched and examined at a magnification suitable to identify the target area prior to specimen manufacture. Where separate macrosections are prepared, their positions along the weld shall be recorded.

Examination of the macrosections shall be used to establish that

a) in a through-thickness notched specimen, the intended crack tip is likely to reside in the target area within the central 75 % of the thickness;

b) in a surface-notched specimen, the intended crack tip is no more than 0,5 mm from the target area.

If the desired microstructure is not present, there is insufficient quantity to test, or the crack tip position tolerances cannot be achieved, the weld shall be rejected as unsuitable for testing to the SM criteria. In this case, a new target area may be selected or a new weld prepared. If the bend specimen is to be employed and the specific microstructure is available in sufficient quantity to test, but the crack tip position tolerances cannot be achieved, the shallow-notched specimen testing procedures described in Annex E may be used by agreement between the parties involved.

Owing to the lower crack tip constraint associated with a shallow notch, the fracture toughness value determined from a shallow-notched specimen ($0,10 \leqslant a_o/W \leqslant 0,45$) ($a_o$ = initial crack length, W = specimen thickness) may be higher than that obtained from a standard notched specimen ($0,45 \leqslant a_o/W \leqslant 0,70$) for the same crack tip microstructure. The significance of this potential difference shall be considered when a shallow-notched specimen is to be used.

7.2 Additional requirements for heat-affected zone tests

When the target area is SM in the HAZ, microstructural examinations additional to those in 7.1 shall be conducted on the polished and etched macrosection to determine whether or not the target microstructure is within the central 75 % of the thickness and in sufficient quantity for a successful test.

The measured positions and lengths of the target microstructure may optionally be presented in map form (an example is shown in Annex B). If such a map is drawn, it shall include the full macrosection thickness, showing the positions of the target microstructure. The percentage of target microstructure shall be calculated over the central 75 % of the specimen thickness.

Where surface-notched specimens are selected, the macrosection shall be used to confirm that the target microstructure is present within the range $0,45 \leqslant a_o/W \leqslant 0,70$.

If it is considered unlikely that the fatigue crack tip is placed in accordance with the SM acceptance criteria, then consideration shall be given to revising the target area, preparing a new weld or using a shallow-notched specimen as described in 7.1.

8 Machining

8.1 Tolerances on specimen dimensions

Specimen blanks shall be machined from the product so that the target area identified for testing can be successfully notched. Blanks shall be machined to the dimensional tolerances defined here prior to notching.

Compact specimens shall meet the dimensional requirements of ISO 12135. Standard bend specimens shall conform to Figure 5. Shallow-notched bend specimens (see 7.1, 7.2 and Annex E) shall likewise conform to Figure 5 except that the relative crack length shall be in the range $0,10 \leqslant a_o/W \leqslant 0,45$.

NOTE 1 The dimensional tolerances in Figure 5 for the standard single-edge-notched bend specimen are intentionally less stringent than those of ISO 12135 in order to minimize alteration of the original weld product.

Weld misalignment, weld distortion and specimen blank curvature (for blanks removed from pipe sections) shall conform to the requirements of Figure 6. The straightness requirement of 2,5 % of W on specimen blank sides applies to pipe curvatures (expressed as the ratio of pipe radius to weld thickness) $\geqslant 10$. Welded joints not meeting the specified straightness/misalignment requirements shall be straightened by local bending prior to notching. The points of straightening-force application shall be located at a minimum distance B from the region to be notched. It is essential that the region to be notched is not deformed by straightening operations. A method for straightening specimen blanks from distorted or curved sections is illustrated in Figure 7.

When it is not possible to straighten a specimen blank taken from pipe, a rectangular block of test material may be cut from the pipe and joined by welding to suitable extension pieces. The total length of the test block and extension pieces shall give a specimen of sufficient length to satisfy the curvature requirements of Figure 6. The weld joints shall be sufficiently distant so as not to affect the target microstructure.

NOTE 2 Laser and electron beam welding processes have proved useful in producing narrow joints of low distortion between the test block and the extension pieces.

When a full section thickness specimen is intended, machining shall be kept to a minimum in order to meet the tolerance requirements and the requirements for local compression (see Clause C.2).

Weld overfill shall be machined level with the original product surface.

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

8.2 Notch placement for through-thickness notched specimens

The procedure for through-thickness notch placement for the NP crack plane orientation is illustrated in Figure 8. Both the surface to be notched (side A) and the opposite surface (side B) are ground and etched to reveal the weld and HAZ. A reference line is scribed on each prepared surface A and B normal to the specimen axis ± 5° and along the targeted microstructure. These scribed lines are carried over onto the surfaces normal to the prepared surfaces. A new line is then constructed equidistant between the carried-over lines. This line is used to delineate the intended plane of the notch to be machined into surface A.

NOTE This procedure is designed to ensure that the final crack tip is in the targeted microstructure (especially if it is the HAZ) when the specimen axis in not perpendicular to the weld direction and $a_0/W = 0{,}5$. If $a_0/W \neq 0{,}5$, the line constructed to delineate the intended plane of the machined notch is adjusted laterally to ensure that the final crack tip is in the targeted microstructure.

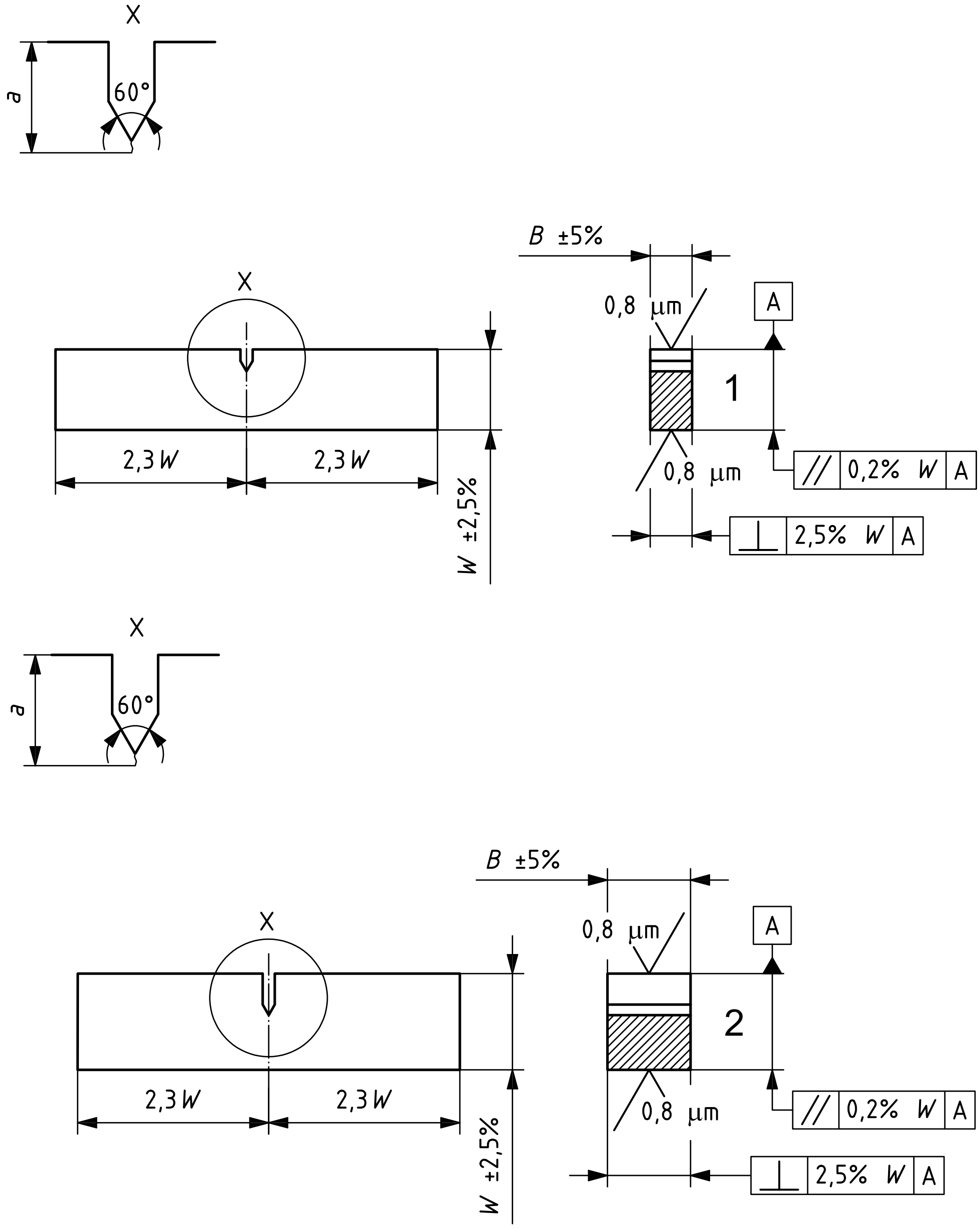
8.3 Notch placement for surface-notched specimens

The procedure for surface-notch placement for the NP crack plane orientation is illustrated in Figure 9. The side surfaces (those at right angles to the surface to be notched) are ground and etched to reveal the weld metal and HAZ. Reference lines are scribed upwards from the selected target-microstructure area to the surface to be notched. Perpendiculars emanating from the scribe lines (normal to the specimen axis ± 5°) are marked (again by scribing) on the surface to be notched. A new line is constructed equidistant between the two lines. This line is used to delineate the intended plane of the machined notch.

NOTE This procedure is designed to ensure that the final crack tip, at the specimen mid-thickness, is in the targeted microstructure when the specimen axis is not perpendicular to the weld direction.

8.4 Notch machining

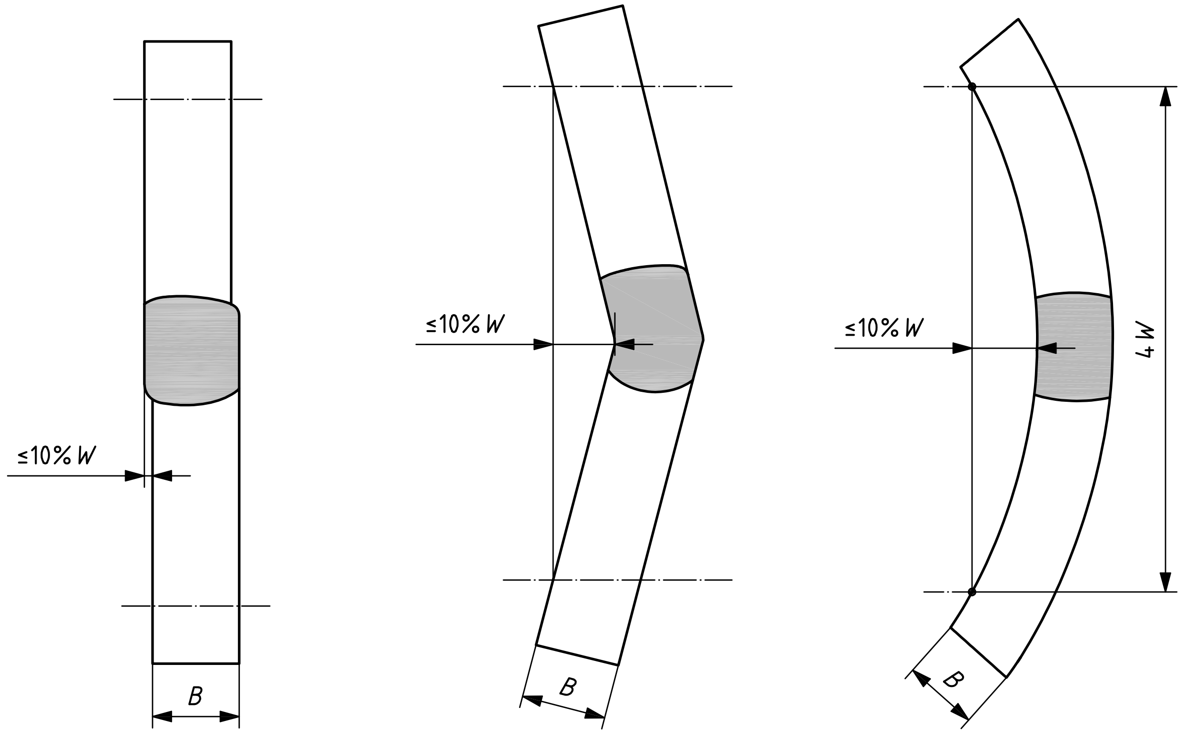
Notch machining shall follow the guidelines of ISO 12135.



1 rectangular-section specimen
width = W
thickness = B = 0,5W
crack length = a = 0,45W to 0,7W
loading span = 4W
notch width = 0,065W_{max}
specimen straightness, see Figure 6

2 square-section specimen
width = W
thickness = B = W
crack length = a = 0,45W to 0,7W
loading span = 4W
notch width = 0,065W_{max}
specimen straightness, see Figure 6

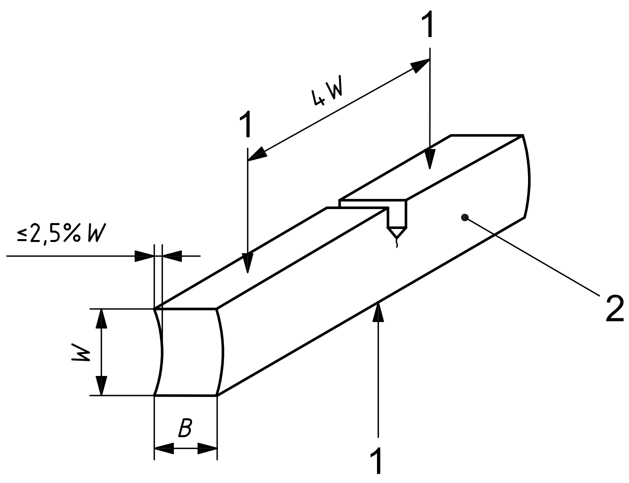
Figure 5 — Proportional dimensions and tolerances for bend specimens



a) **Misalignment**

b) **Misalignment and/or angular distortion**

c) **Curvature**



d) **Curvature**

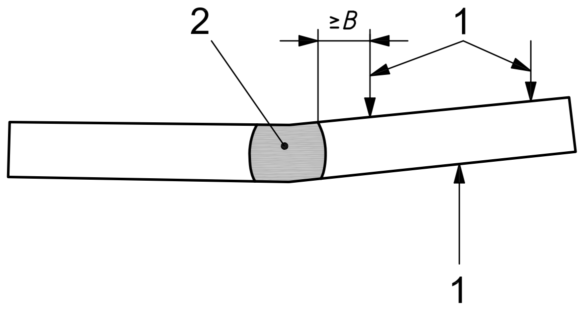
Key

1 loading points

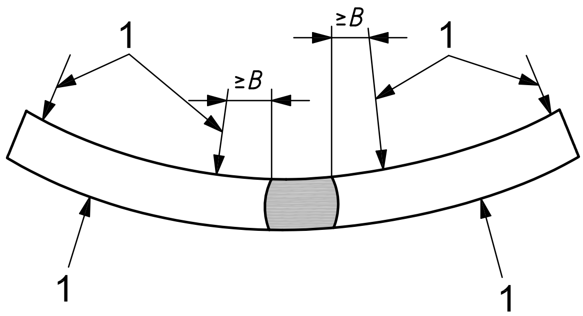
2 curved surface due to tube radius

$4W$ = span

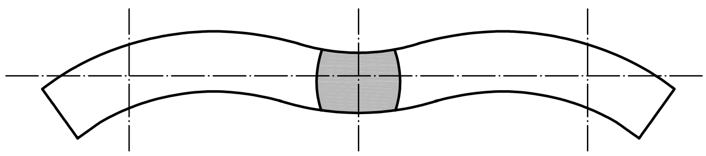
Figure 6 — Tolerances for misalignment, distortion and curvature in single-edge-notched bend specimens



a) To reduce angular distortion



b) To reduce curvature of specimen blank from pipe (each specimen arm straightened separately)



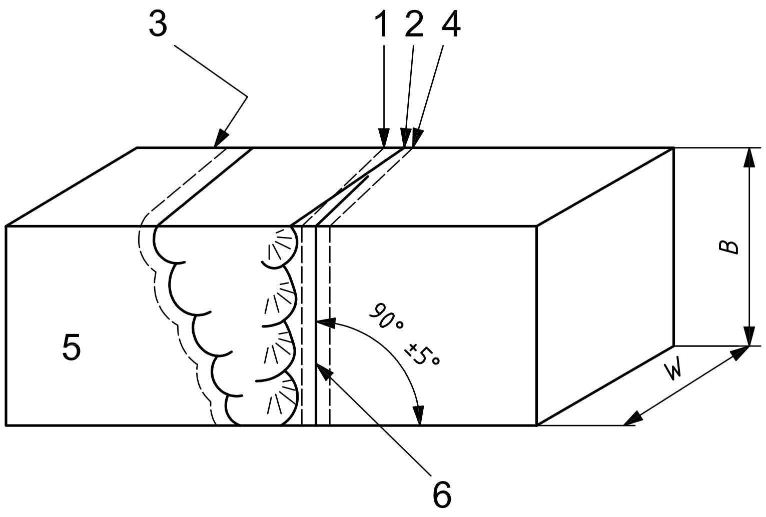
c) Resultant “gull wing” specimen blank shape

Key

1 applied straightening force

2 weld

Figure 7 — Method for straightening bend specimens



Key

1 reference scribe line A

2 fusion line

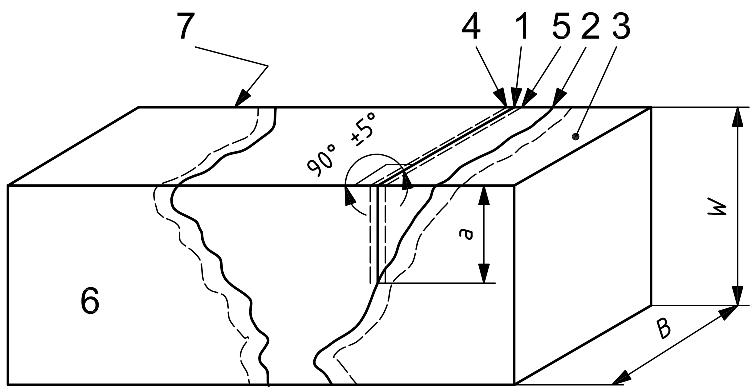
3 side B (unnotched side)

4 reference scribe line B

5 side A (notched side)

6 notch

Figure 8 — Notch placement procedure using reference scribe lines in a through-thickness notched specimen (NP crack plane orientation)



Key

1 notch

2 fusion line

3 notched side

4 reference scribe line B

5 reference scribe line A

6 side A

7 side B

Figure 9 — Notch placement procedure in a surface-notched specimen (NP crack plane orientation)

9 Specimen preparation

9.1 Fatigue precracking

Fatigue precracking shall be carried out in accordance with ISO 12135. For specimens where the intended fatigue crack tip is located in weld metal, the calculation of the maximum fatigue precracking force, F_f, and the 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 is to be located. In all other cases, the properties of the adjacent material with the lowest tensile properties shall be used.

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

When possible, use of the shortest fatigue crack length permitted in ISO 12135 is recommended in order to minimize fatigue crack front bowing and crack deviation from the specified target area.

Problems may occur in meeting the fatigue crack front straightness requirements specified in 12.4, particularly with specimens prepared from as-welded or partially stress-relieved welds. In such instances, the procedures given in Annex C shall be considered.

NOTE 1 The magnitude and distribution of residual stresses in as-welded and partially stress-relieved specimens depend on the material, the welding procedure, the degree of restraint and the post-weld specimen preparation.

NOTE 2 Residual stresses may (or may not) contribute to uneven fatigue crack extension, and may have an effect on the resulting fracture toughness determination.

If the specimen is prepared from a stress-relieved weld, then the procedures in Annex C may not be necessary.

NOTE 3 A straight fatigue crack front may indicate a) low or b) uniform residual stresses in the vicinity of the crack tip.

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 C. When such modifications are made, the fracture toughness result shall be identified as described in 12.4.4.

9.2 Side grooving

Where side grooving is selected, it shall be conducted in accordance with the requirements of ISO 12135.

10 Test apparatus, requirements and test procedure

The apparatus, requirements and procedures for K_{Ic}, δ and J testing shall all be as prescribed in ISO 12135.

11 Post-test metallography

11.1 General

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

Post-test sectioning is not required when the target area is WP.

In the case of brittle fracture, verification that the crack tip did indeed sample the specific microstructure does not guarantee that cleavage initiation necessarily occurred in that microstructure. Further sectioning and metallography may be necessary (when requested by the customer) to identify the microstructure at fracture initiation. The recommended sectioning procedures are the same as those described for the assessment of pop-in and are given in Annex D.

11.2 Through-thickness notched specimens

11.2.1 Sectioning

The through-thickness notched specimen shall be sectioned in a plane perpendicular to the fracture surface, behind the fatigue crack tip, at a position within 2 mm of the maximum fatigue precrack length, and shall include the fatigue crack over the central 75 % of the specimen thickness (B or B_N for side-grooved specimens) (see Figure 10, section A). The cut surface shall be examined metallographically to ensure that the fatigue crack did indeed sample the specific microstructure.

11.2.2 Assessment

The prepared metallographic surface shall be examined to ensure that the fatigue crack tip front sampled the SM and that the SM was located within the central 75 % of the specimen thickness (B or B_N). A microstructural map shall be prepared which records the positions and lengths of the specific microstructure within the central 75 % of the specimen thickness (B or B_N). An example of a specimen notched into the HAZ is shown in Annex B.

11.3 Surface-notched specimens

11.3.1 Sectioning

If the specimen fractures by cleavage, the fracture surface shall be examined at a suitable magnification to identify the initiation site, and at least one section shall be taken as close as possible to this position. If only stable crack extension has occurred, the section shall be taken at the maximum fatigue precrack length. The plane of the section shall be perpendicular to the notch/crack plane (see Figure 11).

Identification of the fracture initiation site may be done visually, but may require the aid of optical microscopy or scanning electron microscopy.

11.3.2 Assessment

The prepared metallographic surface shall be examined to ensure that the fatigue crack tip sampled the SM. If the SM lies ahead of the fatigue crack tip, the minimum separation distance, s_1, shall be measured to an accuracy of ± 0,05 mm [for NQ crack plane orientation, see Figure 12 a)]. If the specific microstructure lies to one side of the fatigue crack tip, the separation distance, s_2, shall be measured to an accuracy of ± 0,05 mm [see Figure 12 b)].

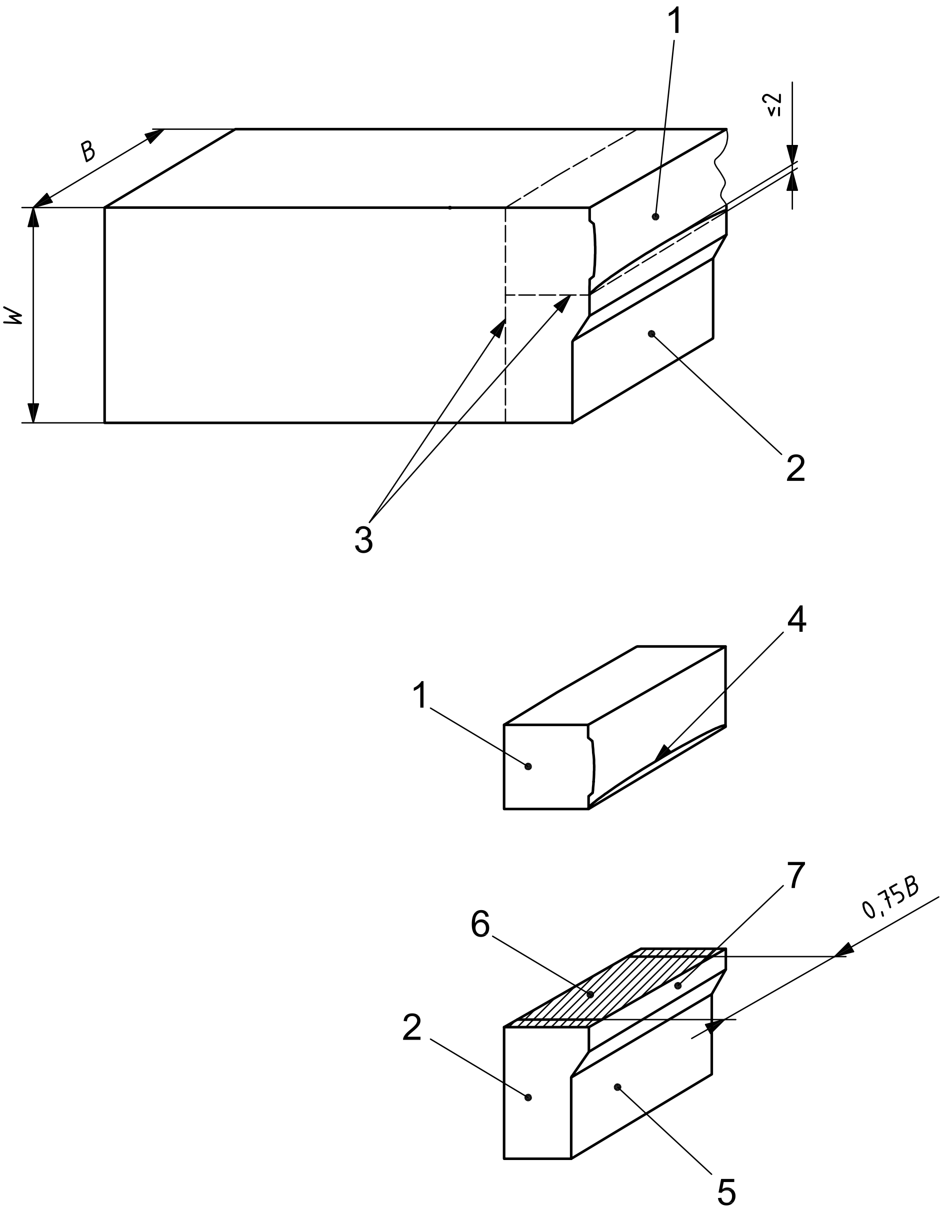
NOTE It might be necessary to section both fracture surfaces to establish these distances.

11.4 Assessment of pop-in

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 D.

NOTE The criteria for the assessment of pop-in described in ISO 12135 are intended for testing homogeneous material and may be inappropriate for welds. Experience indicates that, for weld testing, the size of the pop-in is usually 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.

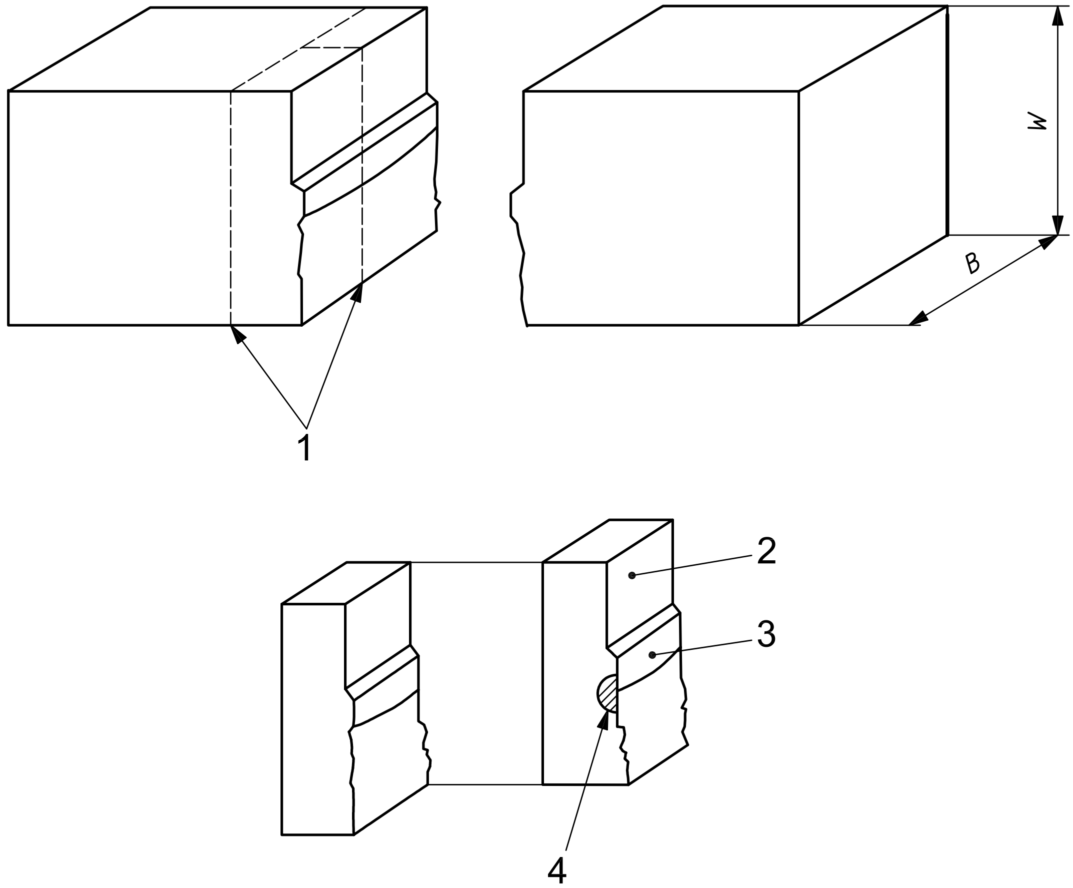
Dimensions in millimetres



Key

1 section B
2 section A
3 cuts
4 fatigue precrack tip
5 notch
6 surface to be examined (polish and etch)
7 fatigue crack

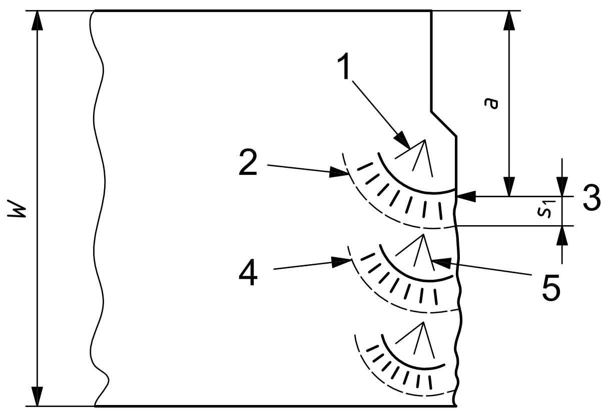
Figure 10 — Post-test sectioning procedure to identify microstructure at fatigue crack in a through-thickness notched specimen



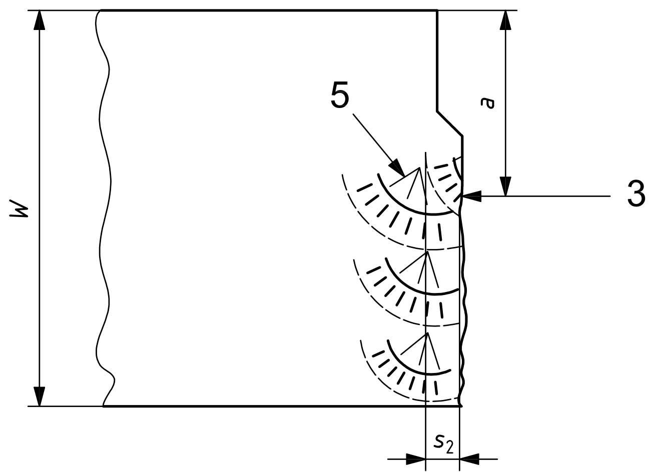
Key

1 cuts
2 notch
3 fatigue crack
4 surface to be examined (polish and etch)

Figure 11 — Post-test sectioning of a surface-notched specimen



a) Target microstructure ahead of fatigue crack tip



b) Target microstructure on one side of fatigue crack tip

Key

1 weld bead
2 reheated weld metal
3 fatigue crack tip
4 reheated weld metal
5 SM (target microstructure)

Figure 12 — Measurement of s_1 and s_2 in a surface-notched SM specimen (NQ crack plane orientation)

12 Post-test analysis

12.1 Choice of tensile properties

When the crack tip is located completely in weld metal, the pertinent tensile properties shall be those determined using an all-weld-metal tensile specimen. When located in, or partially in, the transformed HAZ, the higher of the parent metal and weld metal strengths shall apply.

NOTE Crack tip opening displacement (CTOD) in the HAZ is affected by the strength and size of the HAZ and the adjacent microstructures. Underestimates of CTOD fracture toughness will be made by using the higher of the parent metal and weld metal strengths.

For carbon and C-Mn steels, if the tensile properties of the weld metal and parent metal cannot be measured, they can be estimated (in MPa) from room temperature correlations with measured hardness (in HV10) as follows:

Parent metal [1], $R_{p0,2b} = 3{,}28\ \text{HV10} - 221$, for $160 < \text{HV10} < 495$ (1)

Weld metal, $R_{p0,2w} = 2{,}35\ \text{HV10} + 62$, for $170 < \text{HV10} < 330$ (2)

Parent metal, $R_{mb} = 3{,}3\ \text{HV10} - 8$, for $100 < \text{HV10} < 400$ (3)

Weld metal, $R_{mw} = 3{,}0\ \text{HV10} + 22{,}1$, for $170 < \text{HV10} < 330$ (4)

For ferritic steels, when tension testing below room temperature cannot be done and when the 0,2 % offset yield strength at the low temperature of the intended fracture test is not available, the low-temperature yield strength may be estimated (in MPa) from the room-temperature yield strength using the following relationship[2]:

$$R_{p0,2}\ (\text{at low temperature, } T) = R_{p0,2}\ (\text{at room temperature}) + \frac{10^5}{(491 + 1{,}8T)} - 189 \quad (5)$$

where T is the intended fracture test temperature, in °C, and is greater than −196 °C.

12.2 K_{Ic}

Interpretation of the test record to determine K_{Ic} shall be carried out in accordance with ISO 12135, but with the additional requirements of 12.1 of this International Standard concerning the appropriate choice of $R_{p0,2}$.

12.3 δ and J

Interpretation of the test record to determine δ and J from standard bend or compact specimens shall be carried out in accordance with ISO 12135, but subject to the additional requirements in 12.1. When a shallow-notched bend specimen is employed ($0{,}10 \leqslant a_o/W \leqslant 0{,}45$), interpretation of the test record to determine δ and J shall be carried out in accordance with Annex E.

12.4 Qualification requirements

12.4.1 General

All of the qualification checks listed in ISO 12135 are applicable to this International Standard, but with the following modifications.

12.4.2 Weld-width-to-crack-ligament ratio

For weld metal tests, the δ estimation procedures shall be considered qualified by this International Standard when the following requirements are met[3][4]:

a) for a crack in the centre of the weld, the ratio of the weld width (over the central 75 % of the thickness) to the crack ligament length shall be greater than 0,2, i.e. $2h/(W - a_o) > 0{,}2$ [see Figures 13 a) and 13 b) for through-thickness notched specimens and Figures 14 a) and 14 b) for surface-notched specimens];

b) for a crack offset from the weld centreline, the ratio of the effective weld width (shortest distance between the crack plane and the weld fusion boundary over the central 75 % of the specimen thickness) to the crack ligament length shall be greater than 0,1, i.e. $h/(W - a_o) > 0{,}1$ [see Figures 13 c) and 13 d) for through-thickness notched specimens and Figures 14 c) and 14 d) for surface-notched specimens];

c) for both cases a) and b) above, an additional requirement is that the ratio of the weld metal 0,2 % offset yield strength to the parent metal 0,2 % offset yield strength shall be in the range 0,50 to 1,50, i.e.

$$0{,}50 < \frac{R_{p0,2w}}{R_{p0,2b}} < 1{,}50 \tag{6}$$

For weld metal tests, the J estimation procedures[3][4] shall be considered qualified to this International Standard when the ratio of weld metal to parent metal 0,2 % offset yield strengths is in the range 0,50 to 1,25, i.e.

$$0{,}50 < \frac{R_{p0,2w}}{R_{p0,2b}} < 1{,}25 \tag{7}$$

For HAZ tests, the δ and J estimation procedures of ISO 12135 shall be used (see 12.1 for choice of yield strength for calculating δ). When reporting results, the 0,2 % offset yield strengths of both the parent and weld metal shall be stated.

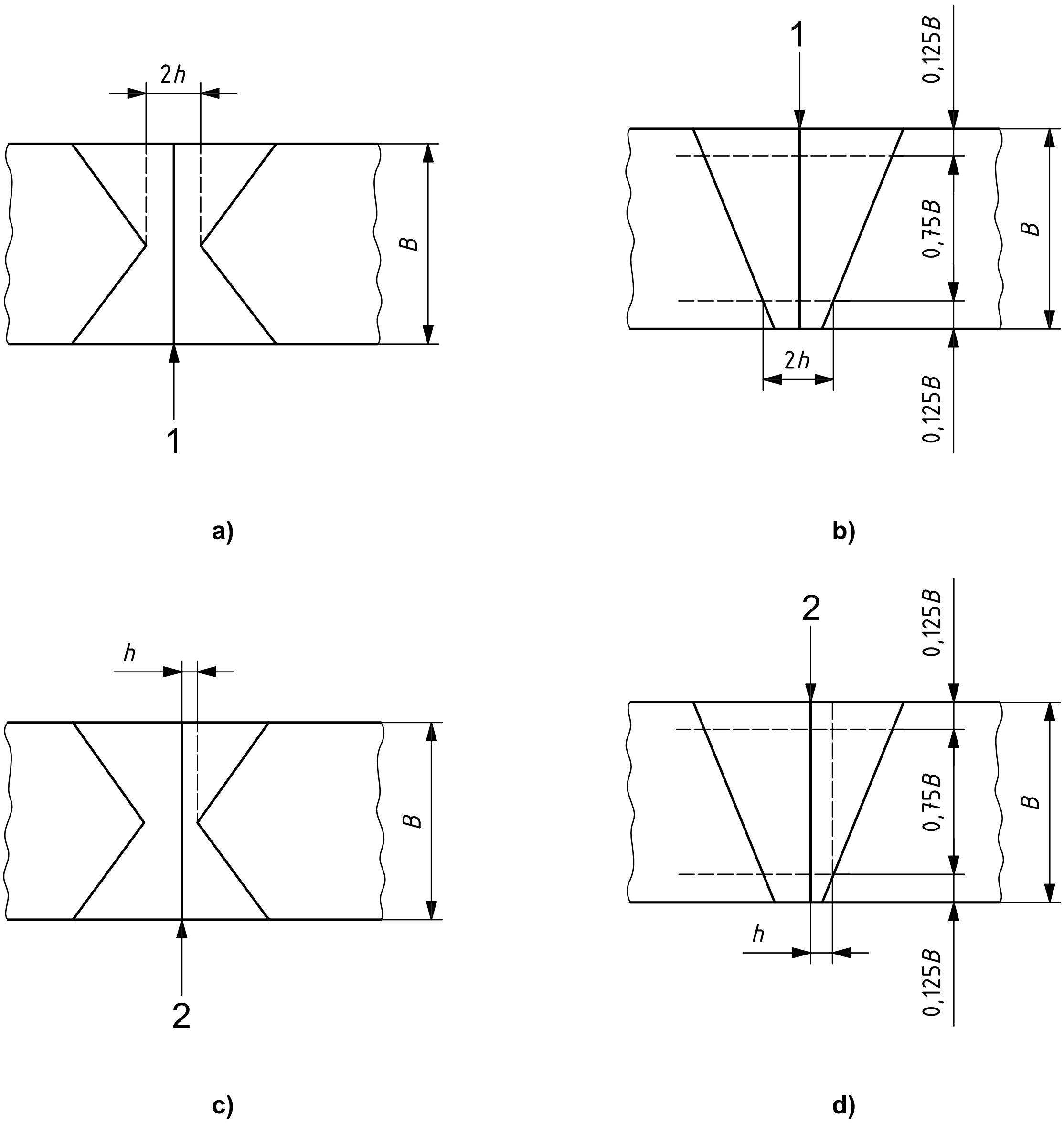
NOTE These estimation and qualification procedures may result in ± 10 % error in weld metal δ or J. Overestimates occur when $R_{p0,2w}/R_{p0,2b} > 1{,}50$ for δ, and $> 1{,}25$ for J; underestimates occur when $R_{p0,2w}/R_{p0,2b} < 0{,}50$ for δ and J [3][4]. When determining HAZ fracture toughness, the J and δ estimation procedures may result in ± 5 % and − 20 % to + 10 % error, respectively, for $0{,}7 < R_{p0,2w}/R_{p0,2b} < 2{,}5$[5].

12.4.3 Crack front straightness

For δ and J tests using bend specimens, the fatigue crack front straightness requirement may be broadened to 0,2 a_o; however, that for compact specimens may not be relaxed. K_{Ic} tests using either compact or bend specimens shall conform entirely to ISO 12135.

NOTE 1 Crack front straightness requirements are based on empirical evidence from bend specimens[6].

NOTE 2 In order to meet the requirements of SM and WP testing, it may not be possible to allow a relaxation of the fatigue crack front straightness requirements, and the more stringent requirements of ISO 12135 may be necessary.



Key

1 crack along weld centreline

2 crack off weld centreline

Figure 13 — Definition of h and $2h$ in through-thickness notched (NP) specimens from double- and single-sided welds

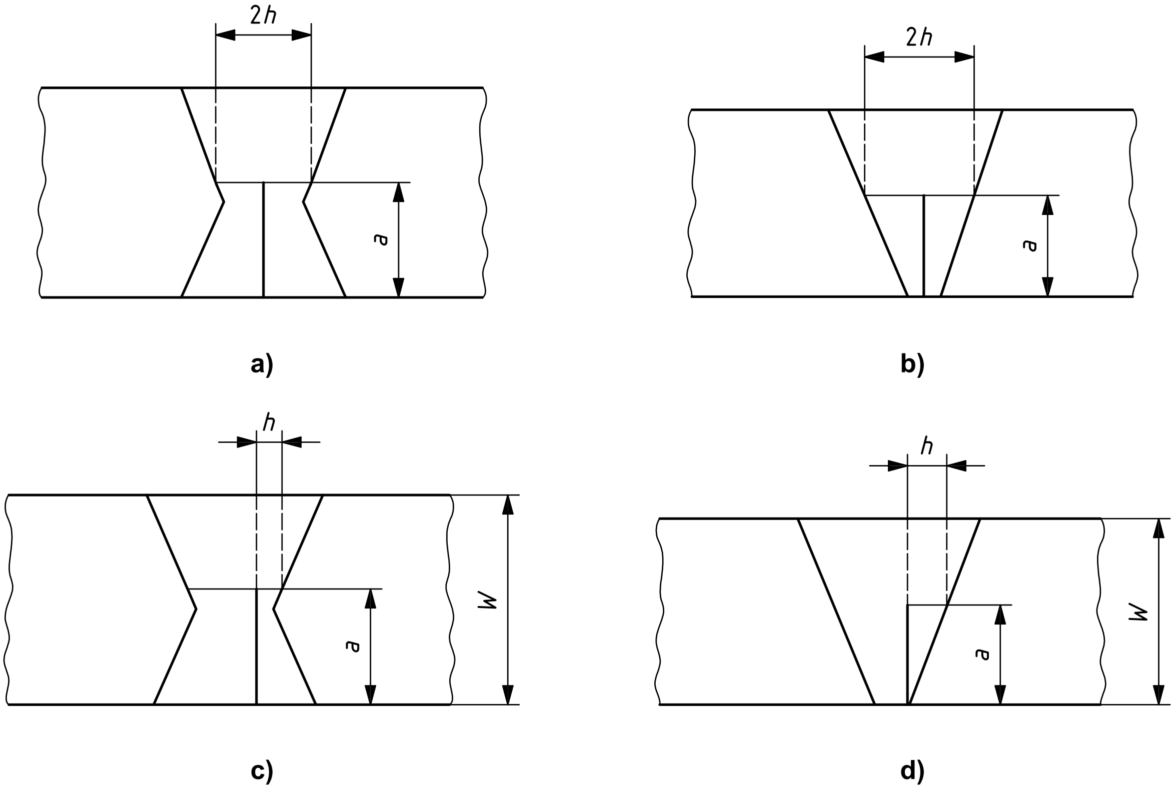


Figure 14 — Definition of h and $2h$ in surface-notched (NQ) specimens from double- and single-sided welds

12.4.4 Symbols used to identify fracture toughness values

In addition to the symbols required by ISO 12135 to identify fracture toughness values, the following shall be used:

a) K, J, δ (no superscripts) shall be used when Annex C modifications to the fatigue precracking procedure have NOT been made;

b) K^M, J^M, δ^M (M as superscript) shall be used to identify results from specimens when the fatigue precracking procedure HAS been modified in accordance with Annex C.

12.4.5 Through-thickness notched specimens

When post-test sectioning and metallographic examination of SM specimens in accordance with 11.2 shows that the fatigue crack front has indeed sampled both the designated target area and, where specified, the designated lengths of specific microstructure within the central 75 % of the specimen thickness (B or B_N), the fracture toughness result shall be considered qualified. When these requirements are not satisfied, the fracture toughness of the specific microstructure has not been determined and the test result shall be considered not qualified.

12.4.6 Surface-notched specimens

When post-test sectioning and metallographic examination of SM specimens in accordance with 11.3 shows either that the fatigue crack tip has indeed sampled the specific microstructure or that the dimension s_1 or s_2 (see 11.3.2) is $< 0{,}5$ mm, the fracture toughness result shall be considered qualified. When these requirements are not satisfied, the fracture toughness of the specific microstructure has not been determined and the test result shall be considered not qualified.

13 Test report

The test report shall be in accordance with ISO 12135, but with the following additional information:

a) whether weld positional (WP) or specific microstructure (SM) notching was used;

b) the crack plane orientation in accordance with Figures 2, 3 and 4;

c) the original thicknesses of the weld and parent metal adjacent to the weld;

d) the pre-test metallography results of macrosection examination (if appropriate);

e) the tensile properties of the weld and parent metal and the method used to derive the values;

f) the effective weld width, h, as appropriate;

g) the method used to achieve a straight fatigue crack front and inclusion of a superscript in the result symbol in accordance with 12.4.4, if appropriate;

h) the assessment of pop-in significance (if appropriate) in accordance with Annex D;

i) whether the result can be considered qualified with respect to crack sampling of the designated target area;

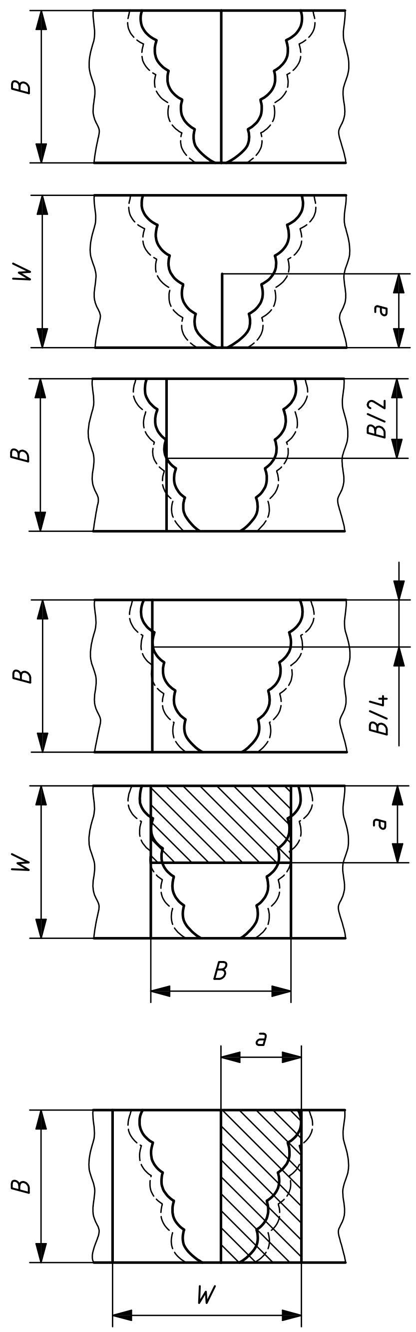
j) the distance s_1 or s_2, as appropriate, for SM notching;

k) whether a shallow-notched bend specimen was used in accordance with Annex E and, if so, the value of a_0/W.

Annex A
(informative)

Examples of notch locations

This annex gives examples of typical locations 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 centreline
ii)	NQ	$B \times B$	Weld metal centreline 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, on weld centreline

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

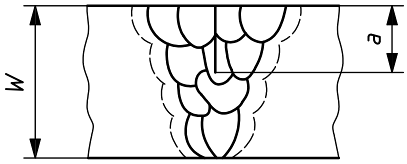
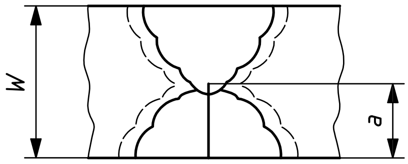
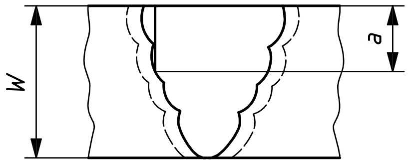
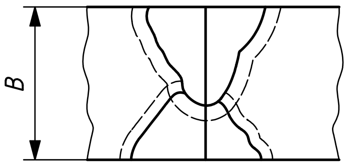
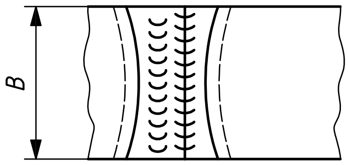
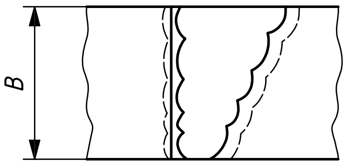
		Orientation	Cross-section proportions (thickness × width	Notch location
i)		NP	$B \times B$	Columnar weld metal on weld centreline
ii)		NQ	$B \times B$	Weld root or second side welded
iii)		NQ	$B \times B$	Grain-coarsened HAZ adjacent to columnar weld metal
iv)		NP	$B \times B$ or $B \times 2B$	Maximum 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 a specific region within the HAZ

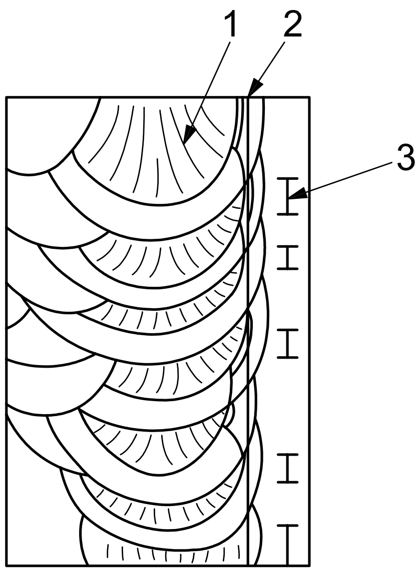
Figure A.2 — Examples of specific microstructure (SM) notch locations

Annex B
(informative)

Examples of pre-test and post-test metallography

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

When SM testing is specified, post-test metallography is necessary to confirm that the target microstructure was present close to the fatigue crack tip, for example, and to confirm the mapping shown in Figure B.2 for section A in Figure 10.



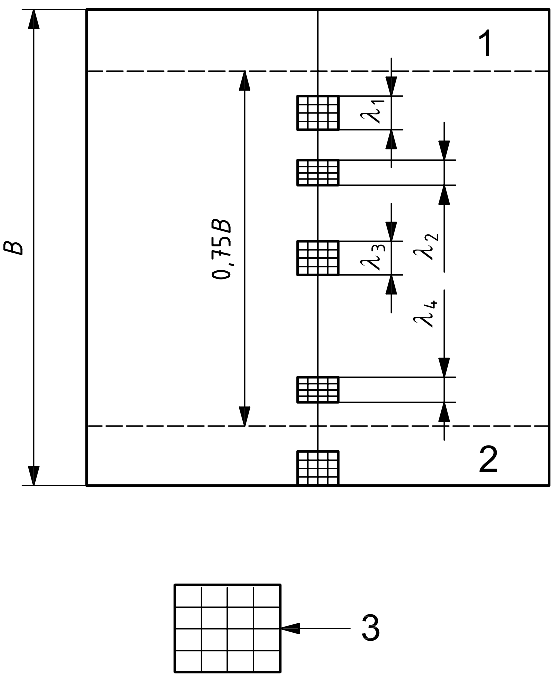
Key

1 columnar weld metal

2 idealized notch line

3 HAZ adjacent to columnar weld metal

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



Key

1 cap

2 root

3 target HAZ

Percentage of specific microstructure (over middle 75 % of thickness) $= \dfrac{\sum_{\lambda_1}^{\lambda_n} \lambda}{0{,}75B} \times 100$

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

Annex C
(normative)

Residual-stress modification and precracking technique

C.1 General

One of the following techniques, specified in Clauses C.2 and C.3, shall normally be used for testing as-welded or partially stress-relieved specimens. By agreement, alternative procedures may be employed if they are documented and validated. The technique used shall be indicated when reporting the test results.

NOTE 1 These techniques are normally unnecessary for welds that have been stress-relieved by post-weld heat treatment.

NOTE 2 In as-welded or partially stress-relieved specimens, residual welding stresses will be present. However, the magnitude and distribution of these stresses may be different from those present in the weld from which the specimens were taken. Residual stresses can result in unacceptable fatigue crack front shapes and, moreover, can affect the determination of the fracture toughness. Experience has shown that local compression conducted prior to fatigue precracking will reduce residual stresses to low and uniform levels[7][8], thus minimizing these effects. An alternative technique which can produce acceptably straight fatigue cracks, especially in thick-section welds where local compression is impractical, is the stepwise high R-ratio fatigue cracking method [9]. However, significant residual stresses may remain in the ligament ahead of the fatigue crack ($W - a_o$), and this may affect the fracture toughness [10].

NOTE 3 Local compression can affect fracture toughness in some materials and under certain testing conditions, but it is difficult to predict which materials are likely to be susceptible. However, experience indicates that it is preferable to accept this risk rather than obtain a result from a specimen with an unacceptable fatigue crack shape.

C.2 Local compression

Local compression[7][8] is applied across 88 % to 92 % of the ligament ($W - a$) in front of the machined notch prior to fatigue precracking and side grooving. The compression shall encompass the notch tip and be applied through 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 to rectangular-section specimens is given in Figure C.1. Depending on the thickness, B, local compression may be applied from one side only or a compression of up to 0,5 % of B may be applied simultaneously on each side of the specimen (see Figure C.1).

Multiple applications of lower compression forces may be employed. In such cases, no dimension of the contact area of the platens shall be less than 0,5B (see Figure C.1). In addition, the final deformation shall be made nearest to the notch tip.

A number of force applications may be necessary to achieve the required plastic deformation, which shall be measured to ± 0,025 mm or ± 0,1 % of B, whichever is larger.

For specimens that have been locally compressed, the dimension B used for the calculation of the 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.

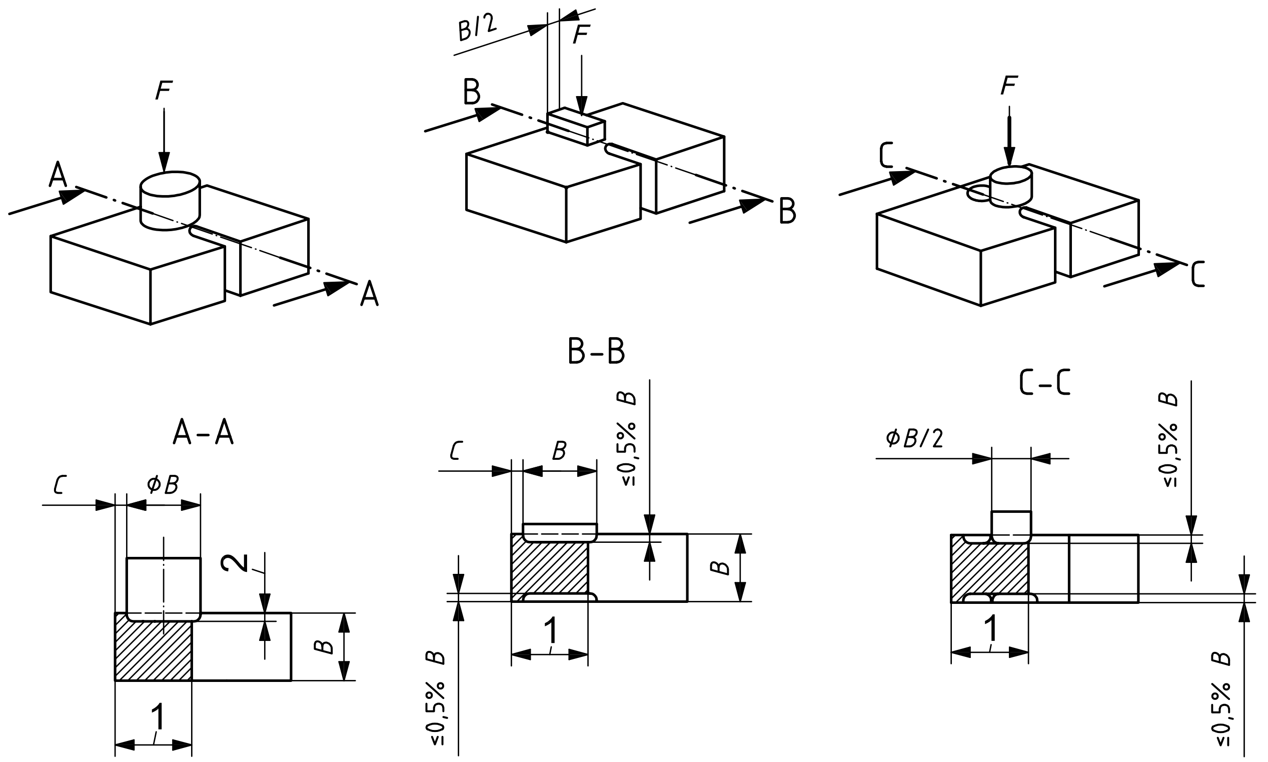
NOTE 2 Experience indicates that a total deformation equal to 1 % of B may be too much for some welds and materials, and straighter crack fronts may be obtained with less. Trials may be necessary to establish the optimum conditions.

NOTE 3 Whichever technique is chosen and where there is little experience with the technique/material combination, it is advisable that the test programme include spare specimens to confirm that the chosen procedure results in acceptably straight fatigue precracks.

C.3 Stepwise high R-ratio

In the stepwise high R-ratio technique[9], fatigue precracking consists of two steps, each at a different fatigue stress ratio, R. For the first step, the stress ratio $R = 0,1$ is used (i.e. the conventional R value for precracking) 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 (maximum value of K) is used in both steps.

NOTE Use of $R > 0,1$ is inconsistent with the fatigue precracking requirements in ISO 12135. Experimental work indicates that fracture toughness may be increased if $R > 0,1$[8][11].



Section A-A	Section B-B	Section C-C
$F = 1,4B^2R_{p0,2}$	$F = 0,8B^2R_{p0,2}$	$F = 0,3B^2R_{p0,2}$

Key

1 W minus machined notch length

2 1 % of B (or 0,5 % of B on each side)

$R_{p0,2}$ is the lower of the values for the parent metal and the weld metal

$C = 8$ % to 12 % of $(W - a)$

Figure C.1 — Alternative local compression treatments

Annex D
(normative)

Assessment of pop-in

D.1 General

This procedure shall be used to assess the acceptability of pop-ins classified as significant in accordance with 11.4.

If the pop-in is assessed as significant in accordance with ISO 12135, post-test fractography and metallography are not required, and the pop-in is considered significant. However, if the pop-in is assessed as not significant in accordance with ISO 12135, the actual significance with respect to this International Standard can be determined from the fractographic and metallographic assessment procedures described in Clauses D.2 to D.5.

All pop-ins shall be considered significant unless the force drop and displacement increase are less than 1 % or it can be demonstrated otherwise by metallographic examination. Values of δ and J measured at the first pop-in event shall be designated δ_{pop} and J_{pop}, respectively.

D.2 Fractography

Both fracture faces shall be examined for evidence of an arrested brittle crack extension, generally in the plane of the fatigue crack, and the maximum crack extension, Δa_{pop}, excluding the SZW, shall be measured (see Figure D.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 ISO 12135.

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 shall be reported, but might not characterize the fracture toughness of the material for the intended crack orientation. A different specimen and crack plane orientation might be necessary to characterize the fracture toughness of the material in the plane of the split[12][13]. Assessment of the structural significance of a split is outside the scope of this International Standard.

D.3 Sectioning and metallography

One or both fracture surfaces containing an arrested brittle crack extension shall be examined by optical and/or scanning electron microscopy to identify the primary fracture initiation site. 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 in a plane perpendicular to the fatigue crack plane as illustrated in Figure D.2 for a through-thickness notched specimen and Figure D.3 for a surface-notched specimen. The sections shall be polished and etched in accordance with usual metallographic practice for microstructural examinations.

D.4 Assessment

The metallographic section taken from a through-thickness notched specimen (see Figure D.4) shall be examined and the length, d_1, of the specific microstructure parallel to the crack front at initiation 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 side-grooved specimens), but not intersected by the crack front, shall be measured and the maximum individual length, d_2, recorded (see Figure D.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 D.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 D.5). More than one section may be taken to assess the dimension d_1.

D.5 Pop-in significance

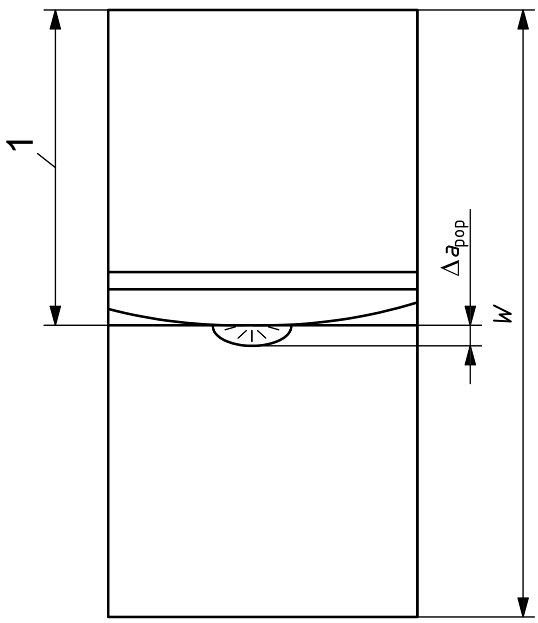
Following metallographic examination, a pop-in shall be considered not significant if

a) for a through-thickness notched specimen: P, calculated in accordance with ISO 12135, is less than 5 % and $d_1 > d_2$;

or

b) for a surface-notched specimen: P is less than 5 % and $\Delta a_{pop} < d_1$.

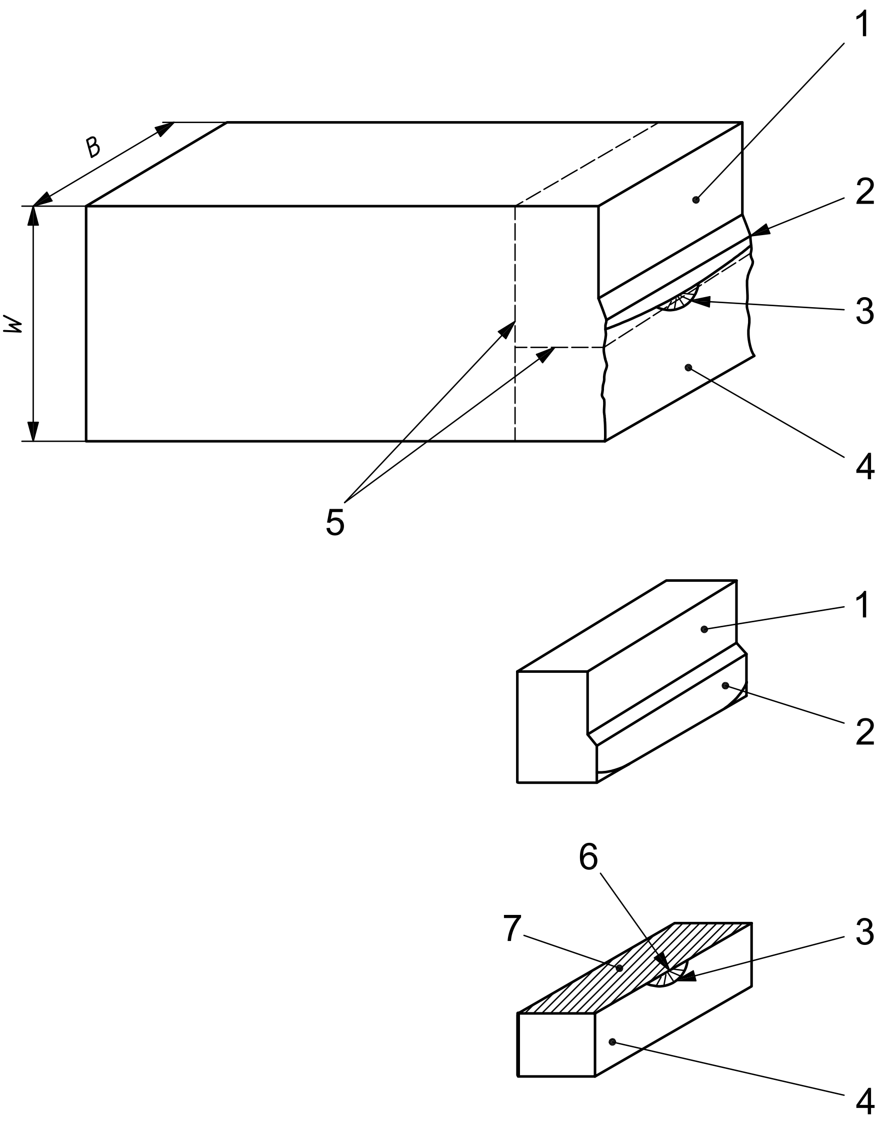
The pop-in shall be considered significant when $d_2 > d_1$ or $d_1 < \Delta a_{pop}$ because a larger pop-in may have occurred if more of the brittle microstructure had been sampled or had been present ahead of the crack tip. Further tests may be necessary to confirm or reject this possibility. A flow chart illustrating the assessment of pop-in is shown in Figure D.6.



Key

1 a or $(a + \Delta a)$

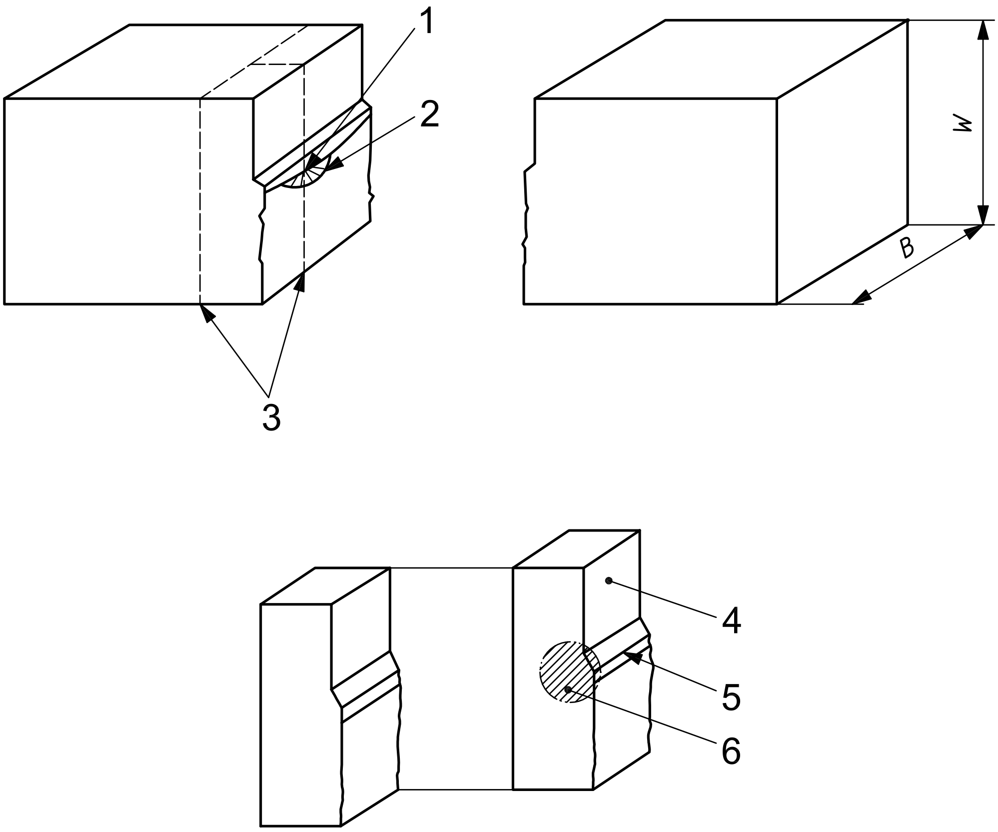
Figure D.1 — Measurement of Δa_{pop}



Key

1 section A
2 fatigue crack
3 arrested brittle crack
4 section B
5 cuts
6 initiation
7 surface to be examined (polish and etch) (see Figure D.4)

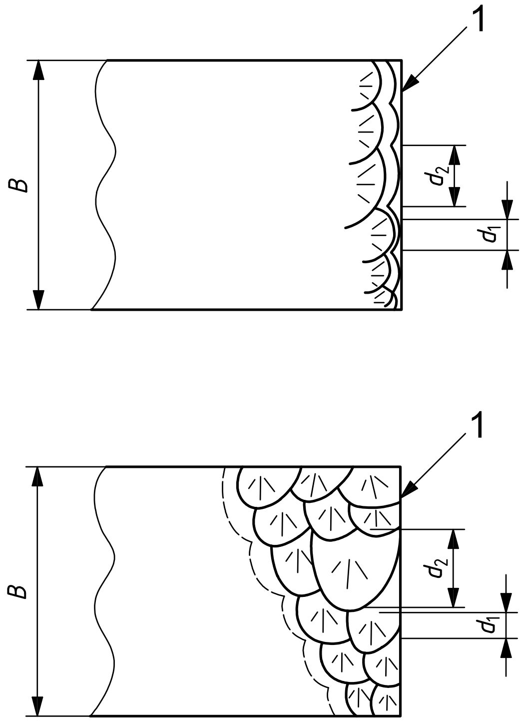
Figure D.2 — Post-test sectioning procedure for identifying fracture initiation microstructure in a through-thickness notched specimen



Key

1 initiation
2 arrested brittle crack
3 cuts
4 notch
5 fatigue crack
6 surface to be examined (polish and etch) (see Figure D.5)

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



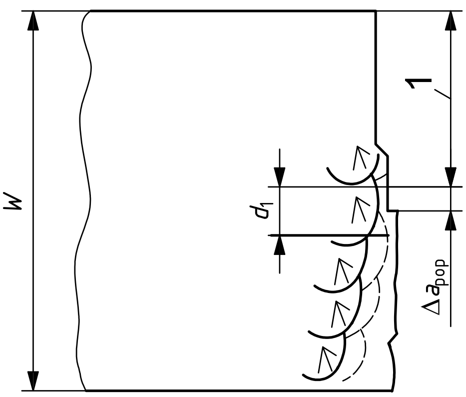
Key

1 fatigue crack

d_1 length of HAZ (upper diagram) or weld metal (lower diagram) sampled by the fatigue crack in the region of fracture initiation

d_2 maximum length of similar HAZ (upper diagram) or similar weld metal (lower diagram) within the central 75 % of B

Figure D.4 — Measurement of d_1 (along crack front) and d_2 (not along crack front) microstructure in section taken from a through-thickness notched specimen (section B in Figure D.2)



Key

1 a or $(a + \Delta a)$

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

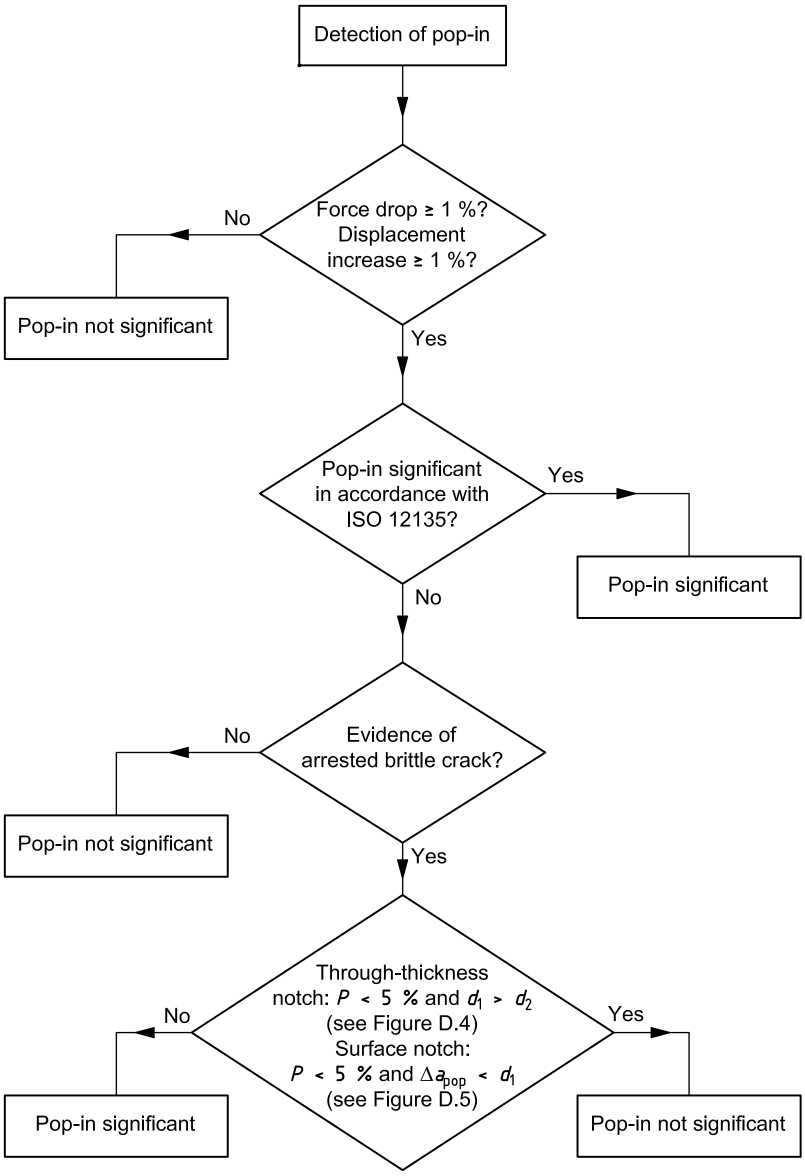


Figure D.6 — Flow chart for assessment of pop-in

Annex E
(informative)

Shallow-notched specimen testing

E.1 General

When the specific microstructure can only be tested using a shallow-notched bend specimen ($0,1 \leqslant a_o/W \leqslant 0,45$), the procedure described in this annex may be used by agreement between the interested parties. The specimen preparation and assessment procedures are the same as those described in the main body of this International Standard, except as modified by Clauses E.2 and E.3 below.

NOTE The nature of welds is such that the specific microstructure may only be present near the surface, which would preclude testing with standard specimens. Use of a shallow-notched bend specimen enables such microstructures to be tested. However, owing to the lower crack tip constraint associated with the shallow-notched specimen, the fracture toughness indication from such a specimen may be higher than that which would have been obtained from a standard notched specimen (i.e. $0,45 \leqslant a_o/W \leqslant 0,70$) for the same crack tip microstructure. This may or may not be significant with respect to the final application, but needs to be recognized by the parties involved.

E.2 Specimen preparation and instrumentation

The bend specimen configuration shall conform to 8.1 and Figure 5, except that the crack length shall be in the range $0,1 \leqslant a_o/W \leqslant 0,45$. The specimen knife edges may be integral, as described in ISO 12135, or attached, as shown in Figure E.1. The crack mouth opening displacement, V, is measured directly by means of a clip-in displacement gauge bearing on integral knife edges. When the knife edges are not integral, but attached instead, the attached knife edges shall be of a configuration such as to support dual clip-in gauges, the outputs of which are used to estimate the crack mouth opening displacement as though it were measured by means of integral knife edges.

NOTE The fatigue crack front straightness requirement of 12.4.3 may be difficult to achieve in a specimen with a_o/W approaching 0,1. However, use of local compression, described in Clause C.2, has been found to be useful in achieving straight fatigue crack front shapes.

E.3 Determination of J and δ

The determinations of J and δ follow the procedures of ISO 12135, except that the calculations are different.

The stress intensity factor relationship for three-point bend specimens is

$$K_o = \left(\frac{S}{W}\right)\frac{F}{\left(B \times B_N \times W\right)^{0,5}} \times g_1\left(a_o/W\right) \quad \text{(E.1)}$$

where

K_o corresponds to K_c, K_u, K_{uc} or K_m calculated for values of force F_c, F_u, F_{uc} and F_m, respectively, which are defined in ISO 12135;

S is the support roller span;

$g_1(a_o/W)$ is the dimensionless stress intensity factor coefficient, specific values of which are tabulated in ISO 12135.

J_o is calculated for the three-point bend specimen[3][4][5][14] from the equation

$$J_o = \frac{K_o^2\left(1-\nu^2\right)}{E} + \frac{\eta_c A_o}{\left(B \times B_N\right)^{0,5}\left(W - a_o\right)} \tag{E.2}$$

where

A_o is the area of the plastic component under the force, F, versus crack mouth opening displacement, V, curve such that

J_c corresponds to J_o, calculated using values of K_c, and F_c and A_c at V_c,

J_u corresponds to J_o, calculated using values of K_u, and F_u and A_u at V_u,

J_{uc} corresponds to J_o, calculated using values of K_{uc}, and F_{uc} and A_{uc} at V_{uc},

J_m corresponds to J_o, calculated using values of K_m, and F_m and J_m at V_m;

and

$$\eta_c = 3,667 - 2,199\left(\frac{a_o}{W}\right) + 0,437\left(\frac{a_o}{W}\right)^2 \tag{E.3}$$

Where attachable knife edges are employed, V is estimated from the outputs of the dual clip gauges, using the following relationship:

$$V = V_1 - z_1\left(\frac{V_2 - V_1}{z_2 - z_1}\right) - 2x\cos\left\{\arcsin^{-1}\left[\frac{1}{2}\left(\frac{V_2 - V_1}{z_2 - z_1}\right)\right]\right\} + 2x \tag{E.4}$$

where

V_1 and V_2 are crack mouth opening displacements measured with clip gauges mounted at distances z_1 and z_2, respectively, above the notched surface (see Figure E.1);

x is the distance indicated in Figure E.1.

δ_o is calculated by substituting J_o from Equation (E.2) into Equation (E.5). If the specimen is notched in the parent metal or the weld metal, Equations (E.5) and (E.6) are used. Equations (E.7) to (E.16) are appropriate to a specimen notched in the HAZ[5][15].

$$\delta_o = \frac{J_o}{m\left(\frac{R_{p0,2b} + R_{mb}}{2}\right)} \tag{E.5}$$

$$m = A_0 - A_1\left(\frac{R_{p0,2b}}{R_{mb}}\right) + A_2\left(\frac{R_{p0,2b}}{R_{mb}}\right)^2 - A_3\left(\frac{R_{p0,2b}}{R_{mb}}\right)^3 \tag{E.6}$$

where

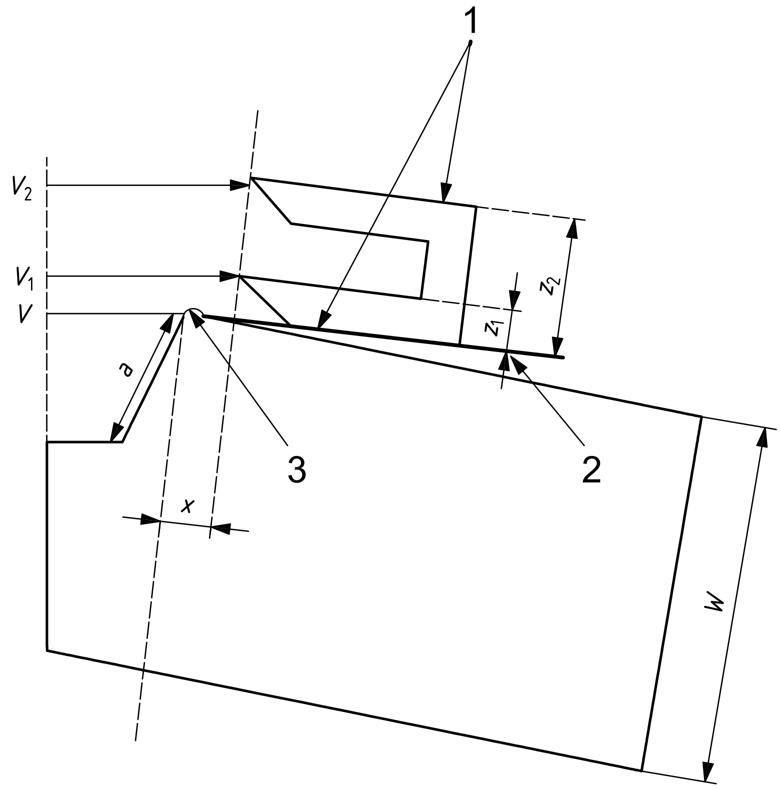
$A_0 = 3,18 - 0,22(a_o/W)$;

$A_1 = 4,32 - 2,23(a_o/W)$;

$A_2 = 4{,}44 - 2{,}29\,(a_o/W)$;

$A_3 = 2{,}05 - 1{,}06\,(a_o/W)$.

For a specimen notched in the weld metal, replace $R_{p0,2b}$ and R_{mb} in Equations (E.5) and (E.6) by $R_{p0,2w}$ and R_{mw}, respectively.



Key

1 knife edges

2 shim

3 micro TIG or laser weld

NOTE 1 The knife edges are attached to a steel shim which is welded to the notch lip using a micro TIG or laser fillet weld.

NOTE 2 Knife edge heights z_1 and z_2 include the height of the steel shim.

Figure E.1 — Design and location of knife edges for dual clip gauges used to estimate crack mouth opening displacement, V

For a specimen notched in the HAZ:

$$\delta_o = \frac{J}{m\sigma_{nom}} \tag{E.7}$$

$$m = -0{,}111 + 0{,}817(a_o/W) + 1{,}36R_{nom} \tag{E.8}$$

$$R_{nom} = \frac{\left(R_{mb} + R_{mw}\right)}{\left(R_{p0,2b} + R_{p0,2w}\right)} \tag{E.9}$$

$$\sigma_{\text{nom}} = \lambda_{\text{u}} R_{\text{p0,2w}} + (1 - \lambda_{\text{u}}) R_{\text{p0,2b}} \quad \text{for } M < 1 \tag{E.10}$$

$$\sigma_{\text{nom}} = R_{\text{p0,2}} \quad \text{for } M = 1 \tag{E.11}$$

$$\sigma_{\text{nom}} = \lambda_{\text{o}} R_{\text{p0,2w}} + (1 - \lambda_{\text{o}}) R_{\text{p0,2b}} \quad \text{for } M > 1 \tag{E.12}$$

$$M = \frac{R_{\text{p0,2w}}}{R_{\text{p0,2b}}} \tag{E.13}$$

$$\lambda_{\text{o}} = 0{,}5 \exp\left[-\left(1 + 0{,}01 n^2\right)\left(M - 1\right)\right] \tag{E.14}$$

$$\lambda_{\text{u}} = 1 - 0{,}5 \exp\left[-\left(1 + 0{,}01 n^2\right)\left(\frac{1}{M} - 1\right)\right] \tag{E.15}$$

$$n = \frac{41{,}34}{\left[1{,}464 + 82{,}68\left(R_{\text{nom}} - 1\right)\right]^{0{,}5} - 1{,}210} \tag{E.16}$$

NOTE Numerical analyses have shown that these J and δ procedures result in less than 10 % error for $0{,}1 < a_{\text{o}}/W < 0{,}5$ when estimating weld metal fracture toughness for $0{,}75 < M < 1{,}50$ and $h/(W - a_{\text{o}}) > 0{,}1$[3][4] and when estimating HAZ fracture toughness for $0{,}70 < M < 2{,}50$ and $0{,}5 < h/B < 1{,}25$[5][15].

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