
**Metallic materials — Steel — Method
of test for the determination of
brittle crack arrest toughness, K_{ca}**

*Matériaux métalliques — Acier — Méthode d'essai pour déterminer
la ténacité à la rupture fragile, K_{ca}*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Fatigue, fracture and toughness testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides a test method for determining the crack arrest toughness of steels. Experimental methods of crack propagation and arrest are documented in Reference [1]. Among these, ASTM E1221 [2] is a test method to evaluate lower bound crack arrest toughness, K_{Ia} , under plane strain conditions. On the other hand, crack arrest testing methods using wide plates were developed in the 1950s [3] and have been used for assessing the crack arrest capabilities of cryogenic tanks [3] and pressure vessels [4][5][6]. In recent years, these methods have been extensively used for evaluating the crack arrest toughness of ship steels [7].

The wide plate crack arrest test is intended to evaluate the arrest toughness, K_{ca} , of steel plate at its thickness of actual use and not the lower bound arrest toughness, K_{Ia} . However, the relationship between the two arrest toughness values has been investigated [4][6]. It was shown that K_{Ia} and K_{ca} values agreed at lower bound of K_{ca} . Moreover, the wide plate crack arrest tests were shown to evaluate the arrest toughness at a higher temperature range at which K_{Ia} evaluation is impossible. The theoretical background of crack arrest toughness testing with a temperature gradient is described in References [8] and [9].

This document provides a test method for the determination of brittle crack arrest toughness of steel by using wide plates with a temperature gradient.

The test method can be summarized as follows: after setting a temperature gradient across the width of a test piece and applying uniform stress to the test piece, the test piece is struck to initiate a brittle crack from a mechanical notch in either edge of the test piece and cause crack arrest after propagating in the width direction (temperature gradient type arrest testing). [Annex A](#) describes typical devices and a method of setting the temperature gradient on the piece. Using the stress intensity factor, the arrest toughness, K_{ca} , is calculated from the applied stress and the arrest crack length. This value is the arrest toughness at the temperature at the point of crack arrest (arrest temperature). To determine K_{ca} at a specific temperature, such as the design temperature of a structure, the method specified in [Annex B](#) is applicable.

The method described in [Annex C](#) can be used to determine the stress intensity factor for a curved crack, in order to check the validity of a crack propagation path.

As a method for initiating a brittle crack, a secondary loading mechanism can be used (see [Annex D](#)). The arrest characteristics of the test piece can also be evaluated by welding a crack starter plate to the test plate in the width direction to enable a brittle crack initiated from the mechanical notch at the edge of the test piece to propagate in the crack running plate and observing the propagation behaviour of the crack immediately after entering the test plate (see [Annex E](#)).

The method explained in [Annex F](#) can be used to determine the dynamic behaviour of crack propagation and measure the dynamic strain of a test piece.

Metallic materials — Steel — Method of test for the determination of brittle crack arrest toughness, K_{ca}

1 Scope

This document specifies a test method for the determination of brittle crack arrest toughness.

It is applicable to ferritic steel base metals exhibiting ductile to brittle transition behaviour. Applicable materials are rolled steel plates. It is intended for materials with a tensile strength of 950 MPa or less and a test piece thickness of 200 mm or less. The range of arrest temperatures is between $-196\text{ }^{\circ}\text{C}$ and $+100\text{ }^{\circ}\text{C}$. This document can be applied to flat rolled steel plates but not to flattened steel pipes because the flattening can cause changes in arrest toughness.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1

brittle fracture

fracture with predominantly cleavage

3.2

arrest

sudden halt of a propagating *brittle crack* (3.4)

3.3

arrest toughness

materials resistance against *brittle crack* (3.4) propagation expressed in terms of stress intensity factor

3.4

brittle crack

crack propagating at approximately 300 m/s or more due to a *brittle fracture* (3.1)

3.5

arrest temperature

temperature at the point where a *brittle crack* (3.4) is arrested in the temperature gradient type *arrest toughness* (3.3) test

3.6

test piece

flat steel plate in which *arrest toughness* (3.3) is to be evaluated

3.7

tab plate

thick end inserted for transferring force from a testing machine

3.8

extension plate

flat plate welded between the *test piece* (3.6) and *tab plates* (3.7)

3.9

integrated test piece

weld assembly of *test piece* (3.6), *extension plates* (3.8) and *tab plates* (3.7)

3.10

loading pin

pin used for the transfer of the force from the testing machine into the *integrated test piece* (3.9)

3.11

distance between loading pins

distance between the centres of the *loading pins* (3.10) inserted into the holes of the *tab plates* (3.7)

3.12

impact energy

energy applied to a wedge placed on a notch formed at the edge of a *test piece* (3.6) to initiate a *brittle crack* (3.4)

3.13

crack branching

case when two or more cracks form during initiation or propagation of a *brittle crack* (3.4)

Note 1 to entry: Secondary cracks that are not a main crack are called branch cracks.

3.14

main crack

crack with the longest propagation length when *crack branching* (3.13) occurs

3.15

shear lip

fracture surface generated by ductile fracture adjacent to the front and back surfaces of a steel plate

3.16

stretch zone

plastic deformation at tip of the arrested crack front

4 Symbols

For the purposes of this document, the symbols given in Table 1 apply.

Table 1 — Symbols used in this document

Symbol	Unit	Designation
a_{ca}	mm	Arrest crack length
B	mm	Test piece thickness
B_{ex}	mm	Extension plate thickness
^a 0,031 6 MPa m ^{1/2} = 1 N mm ^{-3/2} = 0,031 6 MN m ^{-3/2} .		

Table 1 (continued)

Symbol	Unit	Designation
B_{tb}	mm	Tab plate thickness
E	MPa	Modulus of elasticity
E_i	J	Impact energy
E_s	J	Strain energy stored in a test piece
E_t	J	Total strain energy stored in extension plates and tab plates
F	MN	Applied force
K	MPa m ^{1/2} (N/mm ^{3/2}) ^a	Stress intensity factor
K_{ca}	MPa m ^{1/2} (N/mm ^{3/2}) ^a	Arrest toughness
L	mm	Test piece length
L_p	mm	Distance between loading pins
L_{ex}	mm	Extension plate length
L_{tb}	mm	Tab plate length
R_p	MPa	Yield stress at room temperature
T_{ca}	°C	Arrest temperature
T_{caK}	K	
W	mm	Test piece width
W_{ex}	mm	Extension plate width
W_{tb}	mm	Tab plate width
x_a	mm	Coordinate of the main crack tip in the width direction
x_{br}	mm	Coordinate of the longest branch crack tip in the width direction
y_a	mm	Coordinate of the main crack tip in the loading direction
y_{br}	mm	Coordinate of the longest branch crack tip in the loading direction
σ	MPa	Applied stress in unnotched cross section

^a 0,031 6 MPa m^{1/2} = 1 N mm^{-3/2} = 0,031 6 MN m^{-3/2}.

5 Test equipment

5.1 General

The following provides specifications for the testing machine needed for conducting the test. The testing machine is used to apply tensile force to an integrated test piece, and the impact equipment is used to initiate a brittle crack on the test piece.

5.2 Testing machine

5.2.1 Force implementation

Tensile force to an integrated test piece can be either hydraulically or mechanically applied using either force or displacement control.

5.2.2 Calibration of the load cell

Load cells shall be calibrated to check the accuracy of force measurement. The force-measuring system of the testing machine shall be calibrated in accordance with ISO 7500-1, class 1, or better.

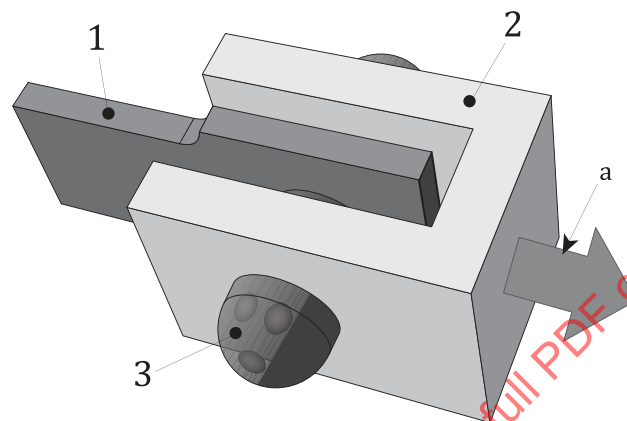
The accuracy of the load cells shall be 1 % of the full scale or less.

5.2.3 Force measurement

Force is measured using a calibrated load cell attached to the testing machine.

5.2.4 Method for force transfer to integrated test piece

The force applied to an integrated test piece by the test machine shall be via a clevis pin type loading method as shown in [Figure 1](#). Centres of the loading pins at both ends shall align with the neutral axis of the integrated test piece.



Key

- 1 integrated test piece
- 2 load clevis
- 3 pin
- a Force.

Figure 1 — Method for loading an integrated test piece through loading pins

5.2.5 Loading direction

The test machine may be either horizontal or vertical. In the case of the horizontal direction, the test piece surfaces shall be placed either perpendicular or parallel to the ground. However, when using the parallel position, care should be taken to ensure that the temperature difference between the top and bottom surfaces of the test piece is within the values specified in [7.1.1.2](#).

5.2.6 Distance between the loading pins

The distance between the loading pins, L_p , as defined in [Figure 8](#), shall be $3,4W$ or more for preventing force drop by a reflection of stress wave at the loading pins. Since the distance between the loading pins potentially has an effect on the force drop associated with crack propagation, especially for a long arrested crack, the validity of the test results shall be verified using the method described in [9.1](#)^[11].

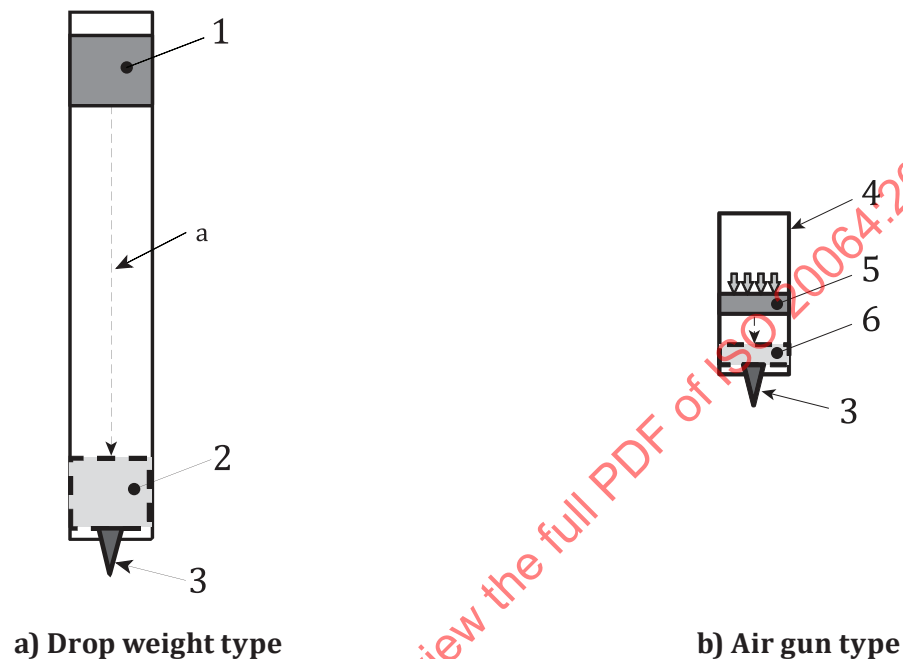
5.3 Impact equipment

5.3.1 Impact methods

Recommended methods for applying an impact force to a wedge mounted on the notch of an integrated test piece include the drop-weight type and the air gun type, as shown in [Figure 2 a\)](#) and [Figure 2 b\)](#), respectively. The drop weight type method applies an impact force to the wedge by freely dropping a weight from a predetermined height. The air gun type method applies an impact force to the wedge by

introducing a predetermined gas pressure into a piston-sealed cylinder, and then releasing the lock of the piston.

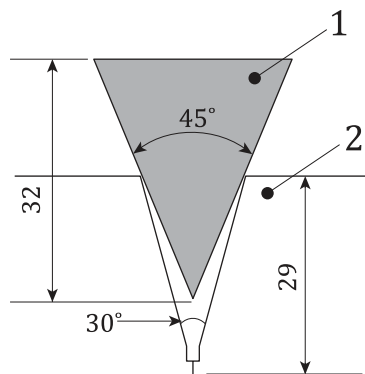
The wedge shall be of sufficient hardness not to plastically deform during impact. The wedge thickness shall be equal to or greater than that of the test piece, and the wedge angle shall be greater than that of the notch formed in the test piece and shall have a shape capable of opening up the notch of the test piece. The recommended shape of the wedge is shown in [Figure 3](#).



Key

- 1 drop weight (before impact)
- 2 drop weight (after impact)
- 3 wedge
- 4 cylinder
- 5 piston (before impact)
- 6 piston (after impact)
- a Free fall of drop weight.

Figure 2 — Impact apparatus

**Key**

- 1 wedge
- 2 test piece

Figure 3 — Recommended wedge shape**5.3.2 Impact energy calculation**

[Formula \(1\)](#) shall be used to calculate the impact energy for the drop weight type method.

$$E_i = mgh \quad (1)$$

where

- m is the mass of the drop weight (kg);
- g is the acceleration of gravity (9,81 m/s²);
- h is the height from the wedge to the drop weight (m).

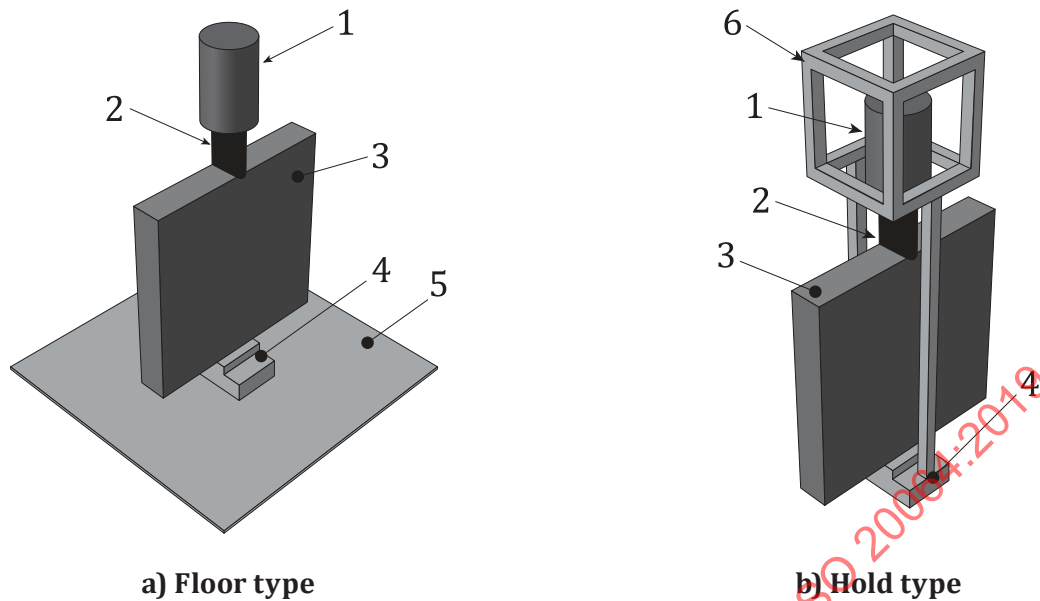
For the air gun type method, an energy conversion table specific to the impact apparatus used for testing shall be used to calculate the impact energy. Impact energy shall be controlled by changing the cylinder pressure.

NOTE The energy conversion table is generally provided by the manufacturer of the air gun type impact apparatus.

Setting of the impact energy value before the test and its validity check after the test are described in [7.2](#) and [9.2](#), respectively.

5.3.3 Reaction force receivers

To suppress the bending moment caused by impact, a reaction force receiver shall be applied opposite the impact edge of the integrated test piece. Two types of recommended reaction force receivers are shown in [Figure 4](#). The floor type, shown in [Figure 4 a\)](#), is fixed on the ground. The hold type, shown in [Figure 4 b\)](#), connects to the frame of the impact apparatus^{[12][13][14]}. Other methods which are equivalent to the methods shown in [Figure 4 a\)](#) and [Figure 4 b\)](#) may be applied.

**Key**

- 1 impact apparatus
- 2 wedge
- 3 test piece
- 4 reaction force receiver
- 5 ground
- 6 frame

Figure 4 — Fixing methods of reaction force receivers

6 Test pieces

6.1 Test piece configurations

The standard test piece configuration is shown in [Figure 5](#). [Table 2](#) shows the ranges of test piece thicknesses, widths and width-to-thickness ratios^{[11][12][15]}.

The test piece length shall be equal to or greater than 500 mm or W , whichever is greater.

A crack starter notch shall be introduced at a test piece edge. The notch may be a mechanical or pressed notch. The pressed notch can be formed by placing a jig having a sharp edge on the bottom of the mechanical notch and applying hydraulic pressure to the jig. The length of the notch shall be 29 mm. No other requirements are specified for the notch shape, but the notch edge shape shall be designed so that a brittle crack is initiated by impact within the impact energy value specified in [9.2](#) but does not initiate during force increase before attaining a specified force value. [Figure 6](#) shows the recommended notch configurations. Side-grooves at the notch-root may be machined on both faces of the test piece to minimize crack deviation and branching. However, the side-groove depth shall be equal to or less than $0,1B$ and the side-groove length measured from the notch-root shall be equal to or less than B or $0,1W$, whichever is smaller. A notch of the same length shall be introduced at the opposite edge to avoid bending moment by matching the net-section centre with the loading axis. In case the side-grooves are applied, however, the notch length at the opposite edge shall be determined so that there is no bending moment.

Table 2 — Dimensions of test pieces

Thickness	Width	Width to thickness ratio
$6\text{ mm} \leq B \leq 200\text{ mm}$	$350\text{ mm} \leq W \leq 1\,000\text{ mm}$ (standard width: $W = 500\text{ mm}$)	$W/B \geq 5$

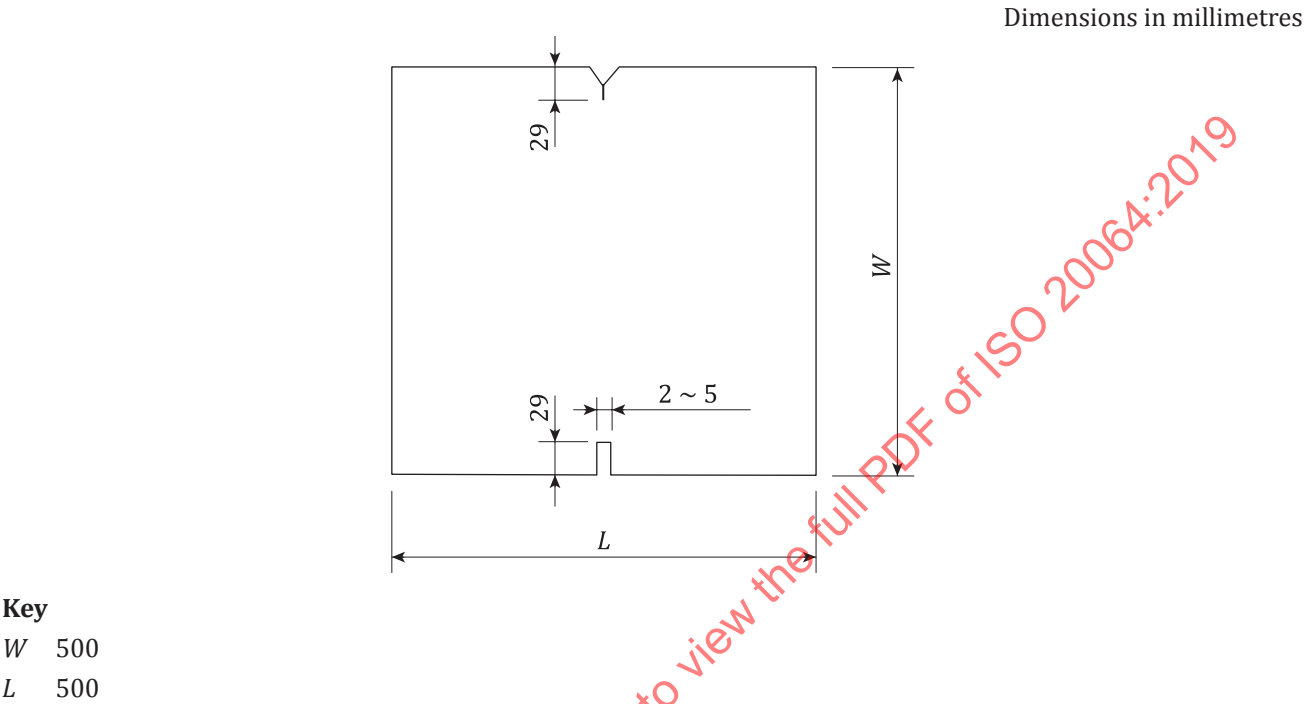
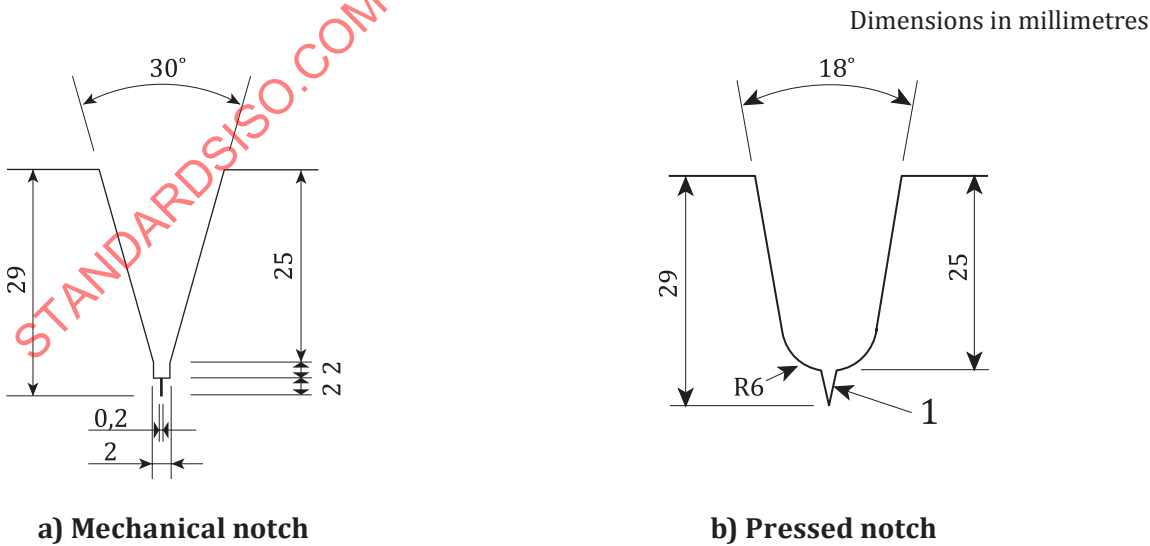


Figure 5 — Standard test piece configuration



Key

1 pressed notch

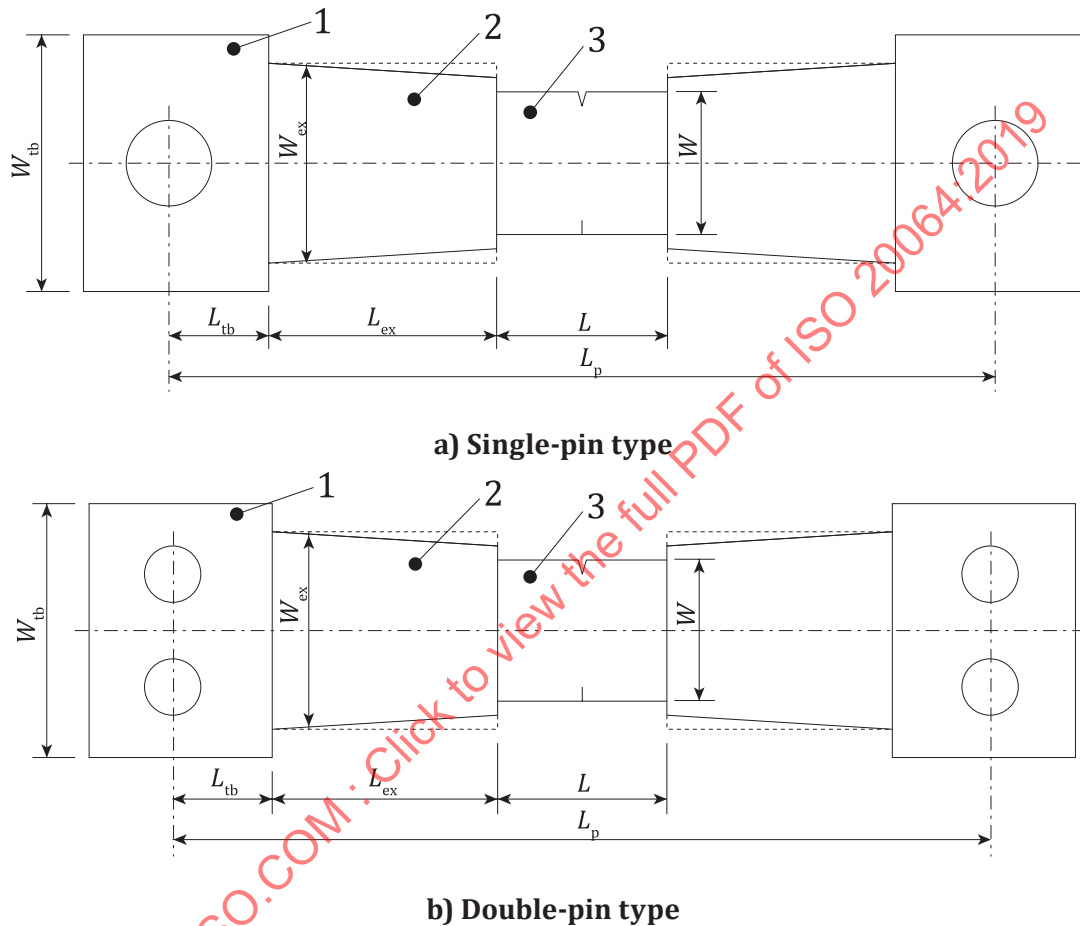
Figure 6 — Recommended notch configurations of test pieces

6.2 Configurations of extension plates and tab plates

6.2.1 General

The definitions of the dimensions of the extension plates and tab plates are shown in [Figure 7](#). Typical examples are shown in [Figure 8](#).

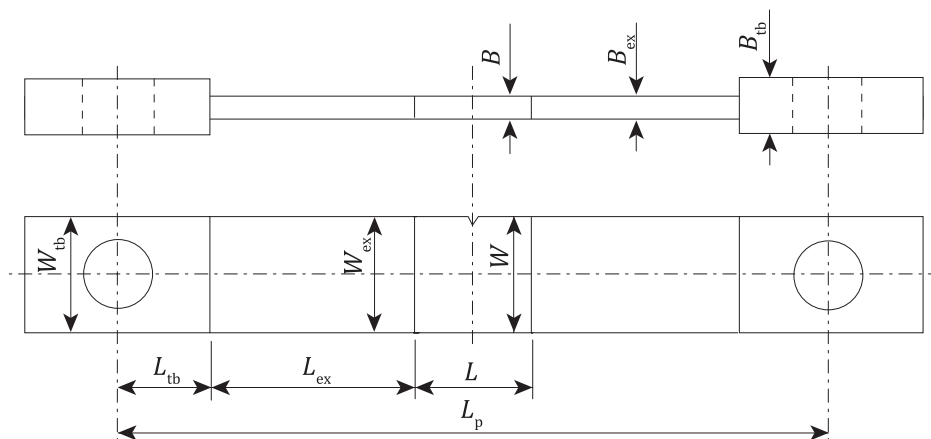
As for loading pins, either the single-pin type or the double-pin type shall be used.



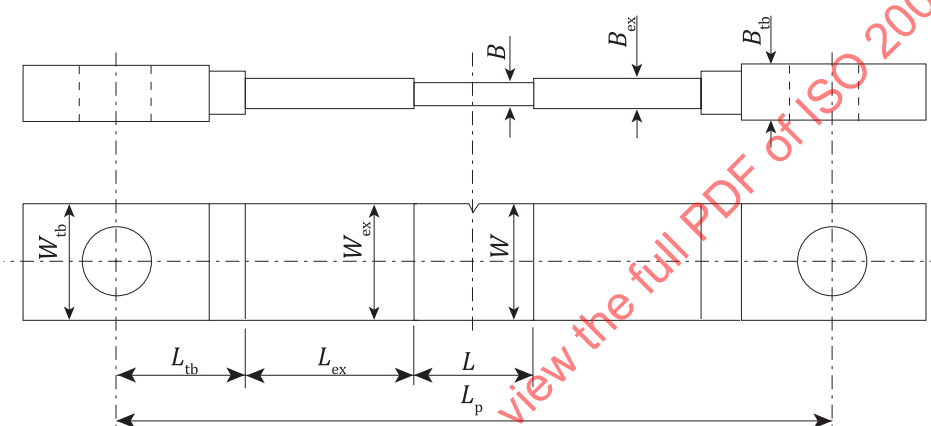
Key

- 1 tab plate (thickness: B_{tb})
- 2 extension plate (thickness: B_{ex})
- 3 test piece (thickness: B)

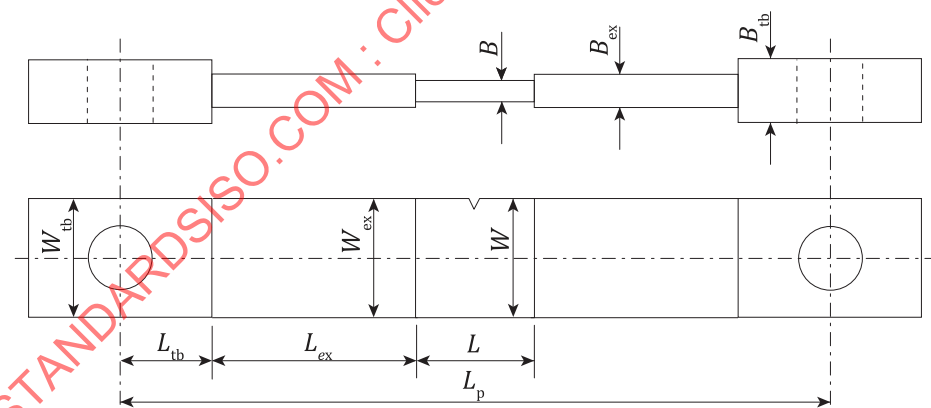
Figure 7 — Definitions of dimensions of extension plates and tab plates



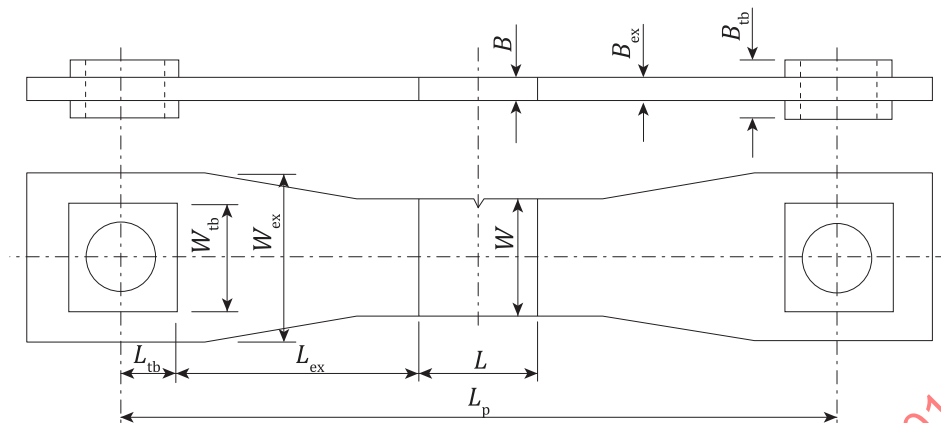
a) Example 1



b) Example 2



c) Example 3



d) Example 4

Figure 8 — Examples of configurations of extension plates and tab plates

6.2.2 Extension plates

The tolerances of extension plate dimensions are shown in Table 3^{[10][11][15]}. When the lengths of the extension plates attached to the two ends of a test piece are different, the shorter length shall be used as the extension length, L_{ex} .

Table 3 — Tolerances of extension plate dimensions

Thickness	$0,8t \leq B_{ex} \leq 1,5t$
Width	$W \leq W_{ex} \leq 2,0W$
Total length of a test piece and extension plates (Total length of a test piece and a single extension plate $L + L_{ex}$)	$L + 2L_{ex} \geq 3,0W$ $(L + L_{ex} \geq 2,0W)$
Length to width ratio	$L_{ex}/W \geq 1,0$

6.2.3 Tab plates

The tab plate width, W_{tb} , shall be equal to or greater than the extension plate width, W_{ex} . The tab plates shall be designed to have sufficient strength to transfer the full magnitude of the applied force to the extension plate and test piece. When the tab plates attached to the two ends of an integrated test piece are asymmetric, the length of the shorter one shall be used as the tab plate length, L_{tb} .

The distance between the pins, L_p , is calculated by using Formula (2):

$$L_p = L + 2L_{ex} + 2L_{tb} \quad (2)$$

6.3 Welding of test piece and extension plates

The test piece, extension plates and tab plates shall be connected by welding. The welds shall have sufficient strength to carry the full magnitude of the applied force.

As shown in Figure 9 a), the flatness (angular distortion, linear misalignment) of the weld between a test piece and an extension plate shall be 4 mm or less per 1 m. However, when preloading is applied, welding residual stress and distortion can be reduced. In this case, flatness may be measured after the preloading. The force of the preloading shall be equal to or less than 95 % the applied force specified in 8.1. As shown in Figure 9 b), the accuracy of the in-plane loading axis shall be 0,5 % of the distance between the pins or less, and the accuracy of the out-of-plane loading axis shall be 0,4 % of the distance between the pins or less.

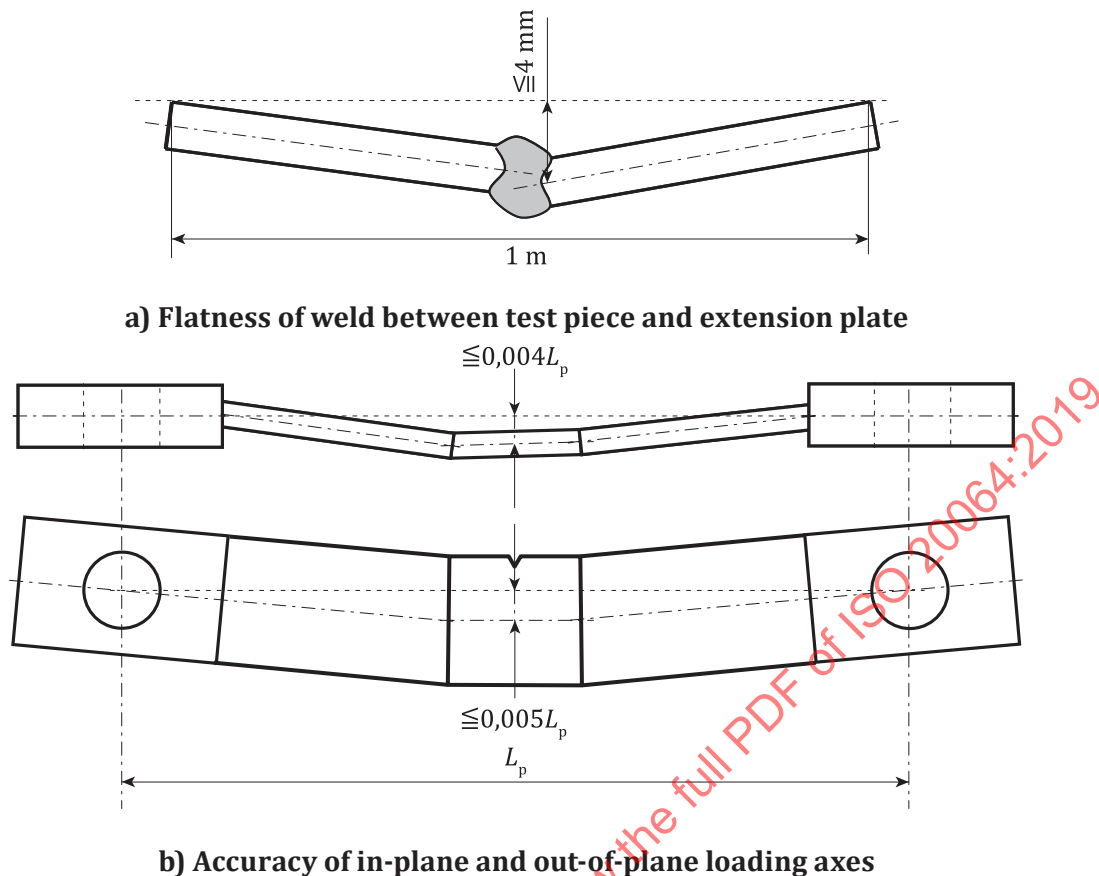


Figure 9 — Dimensional accuracy of weld between test piece and extension plate

7 Test methods

7.1 Temperature control method

7.1.1 Determination of temperature gradient

7.1.1.1 Temperature measurement shall be performed by attaching thermocouples to the test piece. The temperature shall be measured either at the surfaces or at the test piece thickness centre. In the former case, measurements shall be performed on both the front and back faces of the test piece. In the latter case, the temperature measurement shall be performed by attaching thermocouples into holes drilled to the thickness centre of the test piece. The diameter of the holes is recommended as 2,5 mm or less.

A predetermined temperature gradient shall be established across the test piece width by attaching at least nine thermocouples across the front and at least nine across the back face of the test piece for temperature measurement and control. In addition, thermocouples shall be attached at ± 100 mm in the test piece length direction at width central position for temperature measurement to either the front or the back face. Examples of temperature measurement positions are shown in [Figure 10](#). Calibration of temperature measurement by the thermocouples shall be performed by an appropriate method. Accuracy of the temperature measurement shall be $0,2$ °C or less.

The temperature gradient shall be established in accordance with the conditions described in [7.1.1.2](#) to [7.1.1.4](#).

7.1.1.2 A temperature gradient of $0,25$ °C/mm to $0,35$ °C/mm shall be established in a test piece width range between $0,3W$ and $0,7W$. When measuring the temperature at the central position of the test piece thickness, it shall be kept within ± 2 °C for 10 minutes or more, whereas when measuring

the temperatures on the front and back face positions of the test piece, it shall be kept within $\pm 2^\circ\text{C}$ for $[10 + 0,1B \text{ (mm)}]$ minutes or more, considering the time needed for temperature homogenization.

The temperature measurement before 150 mm and after 350 mm is not mandatory; however, in order to keep stable linearity of temperature gradient between $0,3W$ and $0,7W$, it is recommended to monitor the temperature before 150 mm and 350 mm as shown in [Figure 10](#).

NOTE 1 The value of temperature gradient can be evaluated from a temperature distribution curve, as shown in [Figure 16](#).

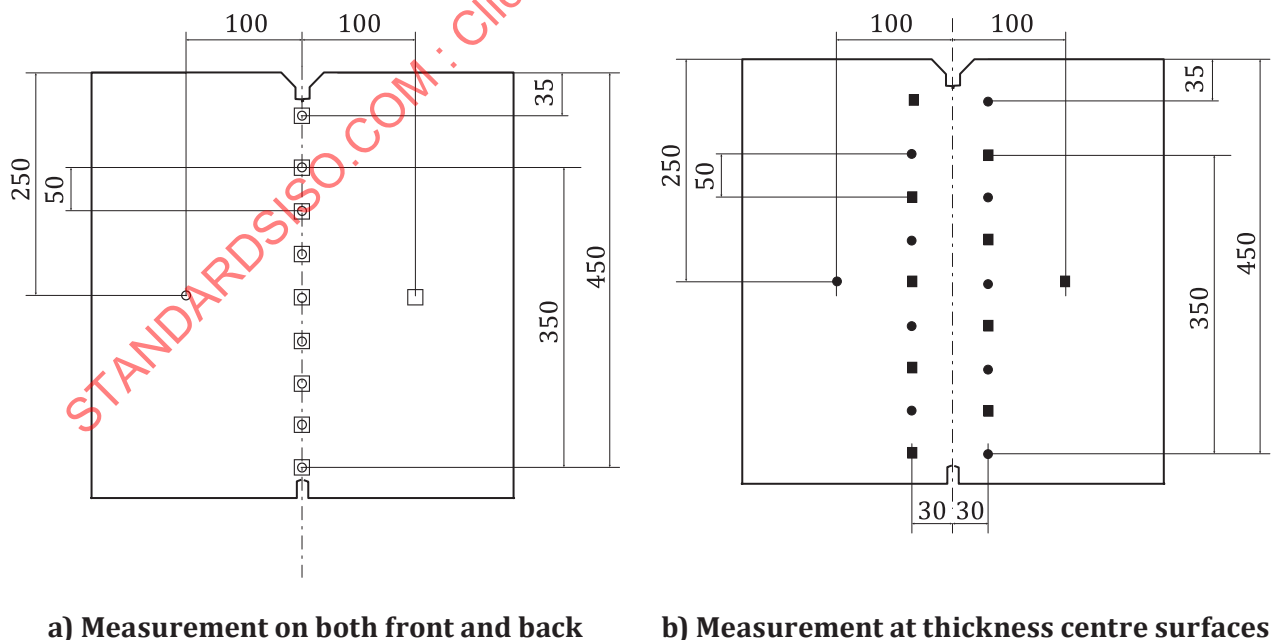
NOTE 2 This document is intended to obtain arrest toughness comparable to that obtained by a test without temperature gradient, e.g. [Annex E](#). If the gradient between $0,3W$ and $0,7W$ is larger than $0,35^\circ\text{C/mm}$, the obtained arrest toughness will be lower than that by a test without temperature gradient^{[10][15]}. Thus, temperature gradient is controlled to be as small as possible within the testable range. In the specified temperature gradient range, the influence of the temperature gradient on K_{ca} can be ignored. If the temperature gradient between $0,3W$ and $0,7W$ is less than $0,25^\circ\text{C/mm}$, crack arrest will be unlikely.

7.1.1.3 At the test piece width central position (i.e. $0,5W$), and in the range of ± 100 mm in the test piece length direction, the deviation from the temperature at the central position in the length direction shall be controlled to within $\pm 5^\circ\text{C}$. However, as shown in [Figure 10 b\)](#), when the temperature is not measured at the central position in the length direction, the average temperature at the closest position $[\pm 30 \text{ mm}]$ in the case of [Figure 10 b\)](#) shall be used as the temperature at the central position in the length direction.

7.1.1.4 At the same position in the width direction, the deviation of the temperature on the front and back surfaces shall be controlled within $\pm 5^\circ\text{C}$.

7.1.2 Method of temperature control and monitoring

To establish the temperature gradients described in [7.1.1](#), a cooling device and a heating device may be used to control the temperatures. Recommended cooling and heating devices are shown in [Annex A](#). Methods other than those may be used provided that the above conditions are met.



Key

Measuring point

- top surface
- bottom surface
- top side (hole)
- bottom side (hole)

Figure 10 — Examples of temperature measurement positions**7.2 Crack initiation methods**

The test piece shall be impacted to initiate a crack so that the crack propagation and arrest event are accomplished under a desired applied stress but not during force increase, unlike quasi-static fracture toughness testing. However, if the impact energy is excessive, it can enhance crack propagation, leading to over-conservative evaluation of arrest toughness because impact energy is not considered in evaluating arrest toughness; see [Formulae \(13\)](#), [\(14\)](#) and [\(15\)](#)^{[12][13][14]}. In that case, the results shall be treated as invalid in accordance with the criteria specified in [9.2](#) and [Formula \(10\)](#). However, this formula shall be evaluated after the test. [Formula \(3\)](#) and [Figure 11](#) can be used to determine the impact energy before conducting the test:

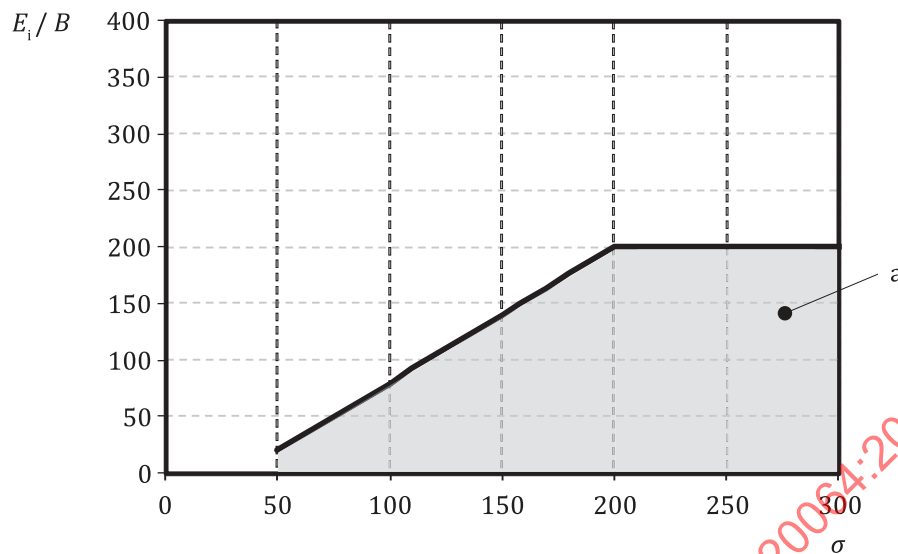
$$\frac{E_i}{B} \leq \min[(1,2\sigma - 40), 200] \quad (3)$$

where min is the minimum of the two values.

No specific minimum impact energy value is specified because the impacting is intended only to initiate the brittle crack, so if very low impact energy is successful in crack initiation, the test is considered valid.

The following methods may be used in case the first impact is unsuccessful.

- a) If no crack initiation has occurred after the impact, the test may be conducted again by applying another impact. The temperature gradient is often distorted by impact and, in that case, the temperature gradient shall be corrected prior to further impact.
- b) If no crack initiation has occurred after the impact, a brittle bead may be placed on the notch tip, in which case the integrated test piece shall be unloaded and warmed to room temperature before the brittle bead is applied. In this case, preloading may be applied at room temperature to prevent autonomous crack initiation before attaining the predetermined applied force. The preloading force shall be 95 % of the predetermined applied force or less. The brittle bead weld metal shall be selected so that it assists brittle fracture initiation from the notch tip.



Key

a Recommended region of impact energy.

Figure 11 — Recommended range of impact energy

8 Test procedures

8.1 Pretest procedures

8.1.1 Install an integrated test piece, a temperature control device and an impact apparatus as per a) to c). The order of a) to c) may be arbitrary.

- Install an integrated test piece in the testing machine.
- Mount a temperature control device on the test piece, as specified in 7.1 and recommended in Annex A.
- Install an impact apparatus, as specified in 5.2, on the testing machine. Place an appropriate reaction force receiver as necessary.

8.1.2 After checking that all thermocouples indicate room temperature, start cooling the test piece. The temperature distribution and the holding time shall be in accordance with 7.1.

8.1.3 Set an impact apparatus, as specified in 5.2.

8.1.4 Apply force, F , to the test piece until the predetermined value is obtained. In case the force is applied by a displacement control device, the force shall be controlled by monitoring a load cell output. This force is applied after the predetermined temperature distribution has been set to the test piece. Otherwise, brittle fracture can be initiated during the cooling process due to thermal stress near the notch-tip. Alternatively, temperature control may be implemented after loading. In this case, cooling shall be slow enough to prevent brittle fracture initiation during cooling due to thermal stress. In the case of temperature control after loading, the cooling rate is recommended as 2 °C/min or less. The applied stress shall satisfy the condition given by Formula (4).

$$\sigma \leq \frac{2}{3} R_p \quad (4)$$

NOTE 1 In this document, measurement outcome is independent of loading rate.

NOTE 2 Correlation of K_{ca} values and temperature shows consistent Arrhenius regression if applied stresses are according to [Formula \(4\)](#). In contrast, if the applied stress is larger than that specified by [Formula \(4\)](#), the test gives a higher arrest toughness value than that tested in accordance with [Formula \(4\)](#) (see [Figure 18](#)). This feature was proven by a numerical analysis^{[8][9]}. This upper bound applied stress/yield stress ratio value was determined from a series of tests using steel plates having R_p from 321 MPa to 416 MPa and plate thickness from 16 mm to 80 mm^[10].

8.1.5 The notch may be cooled further immediately before impact on the condition that the cooling does not disturb the temperature in the range $0,3W$ to $0,7W$. Continuous temperature monitoring is necessary to ensure that there is no disturbance of the temperature distribution. The test temperature in this case shall be the measured temperature obtained from the temperature record immediately before the additional notch cooling.

8.1.6 Record the force value measured by the load cell immediately before the impact.

8.2 Impacting procedures

8.2.1 After holding the predetermined applied force, as determined in [8.1.6](#), for 30 s or more, apply an impact to the wedge using the impact apparatus. In case the force is applied by a displacement control device, the force shall be continuously monitored and controlled by a load cell output. If a crack initiates autonomously and the force value at the time of crack initiation is recorded, the test is valid; use the force value at the time of crack initiation as applied force, F .

8.2.2 Record the force value after the impact.

8.2.3 When the force after the impact is smaller than the applied force by 10 % or more, crack initiation is considered to have occurred and another impact shall not be applied. If there is no indication of crack initiation, another impact may be applied.

8.2.4 An increase in the number of impacts can cause a change in the shape of the notch of the test piece. Since the number of impacts has no effect on the value of arrest toughness, no limit is specified for the number of impacts. However, because the temperature gradient can be disturbed by impact, the test should be conducted again, beginning from temperature control, when applying repeated impact.

8.2.5 If the test piece is still intact, remove the force.

8.3 Post-test operations

8.3.1 Remove the impact apparatus.

8.3.2 Remove the temperature controlling device and any lead wires attached to the test piece. Spray fracture surfaces with rust inhibitor (light oil) if no heat tinting is planned.

8.3.3 Allow the temperature of the test piece to gradually return to room temperature. If a rapid return to room temperature is desired, the test piece may be heated using a heat gun or gas torch or the like. If it is necessary to prevent heat tinting of the fracture surface, this method shall be avoided.

8.3.4 If the test piece is still intact, the fracture surfaces can be separated using one of the following methods.

- a) Most of the remaining ligament can be cut by mechanical means and the resulting ligament pulled apart by the testing machine.

- b) Most of the remaining ligament can be cut using a gas torch, provided that heat tinting of the fracture surfaces is not an issue. This is followed by the resulting ligament being pulled apart by the testing machine.
- c) If the remaining ligament cross-sectional area is small enough, it can be pulled apart by the testing machine without cutting the remaining ligament.

8.4 Observation of fracture surfaces

8.4.1 Photograph the fracture surfaces and crack propagation path. [Figure 12](#) shows examples of photographs.

If the drilled hole for attaching thermocouples appears at the crack arrest position on the fracture surface, the test is invalid.

8.4.2 Measure an arrested crack length at the longest position on the fracture surface and record the result as the arrest crack length, a_{ca} . The arrest crack length shall include the notch length. In cases where a crack deviates from the direction transverse to the loading direction, the length projected along the plane transverse to the loading line, i.e. x_a in [Figure 15](#), is defined as the arrest crack length. In the following cases, however, assess the results according to the methods described for each case.

a) Re-initiation of a crack

In the case where a brittle crack has re-initiated from an arrested crack, ignore the re-initiated crack. Here re-initiation is defined as the case where an arrested crack and re-initiated crack are completely separated by a stretch zone and brittle crack re-initiation from the stretch zone can clearly be observed. [Figure 13](#) shows an example of a re-initiated crack.

In the case where a crack continuously propagates partially in the thickness direction, the position of the longest brittle crack is defined as the arrest position. [Figure 14](#) shows an example of arrest after continuous propagation of a crack partially in the thickness direction.

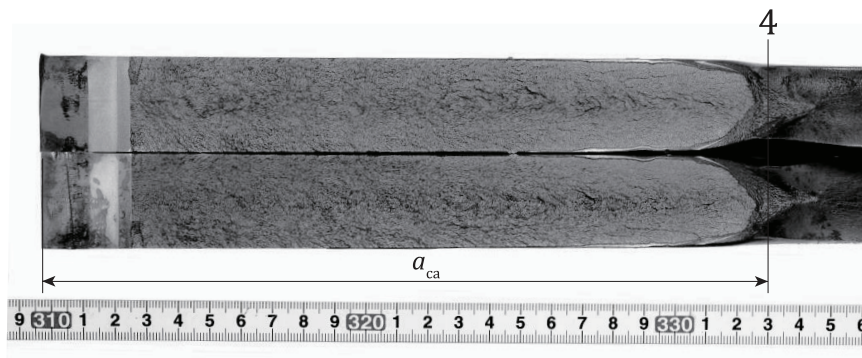
NOTE There is evidence from dynamic measurements of crack gages that crack re-initiation can take place sometime after crack arrest (see [E.2.2](#) [11][15]). The re-initiation is presumed to be caused by a shock wave reflected off the ends of the test piece after the arrest resulting in a sudden increase of tensile stress. This is not always the case for a real structure. Therefore, the first attainment of the crack arrest is adopted in this document.

b) Crack branching

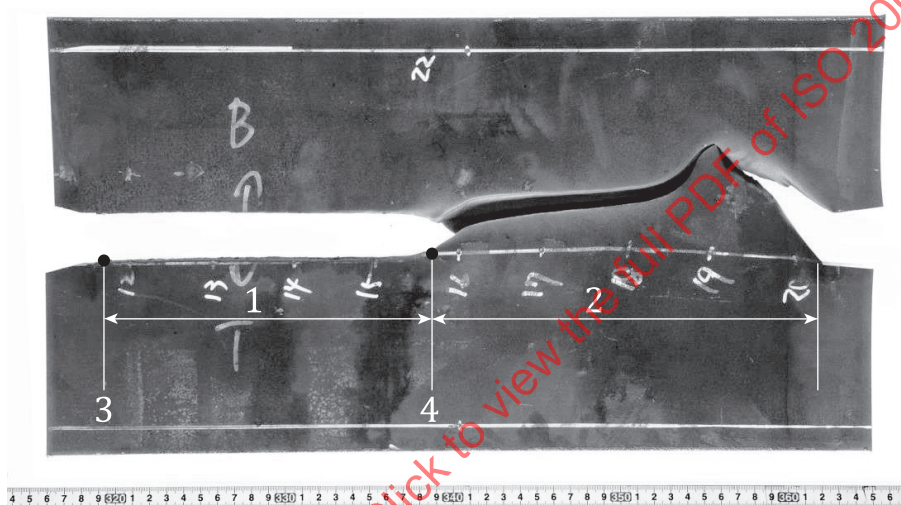
In the case of crack branching, the length of the longest branch crack projected to the plane transverse to the loading line is defined as the branch crack length. More specifically, x and y are coordinates in the test piece width and loading direction, respectively, with the origin at the intersection of the edge of the test piece and the notch; see [Figure 15](#). Let the coordinates of the arrest crack tip be (x_a, y_a) and that of the branch crack tip be (x_{br}, y_{br}) . x_a is equal to the arrest crack length, a_{ca} . Obtain the angle θ for the arrest crack tip, as shown in [Figure 15](#).

8.4.3 Draw a temperature distribution curve (line diagram showing the relation between the temperature and the distance from the test piece edge) from the thermocouple measurement results, and

obtain the arrest temperature, T_{ca} , corresponding to the arrest crack length. An example of temperature distribution curve is shown in [Figure 16](#).



a) Photograph of fracture surfaces

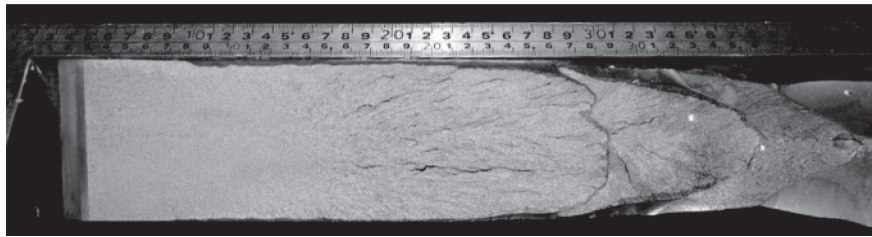


b) Photograph of crack propagation path

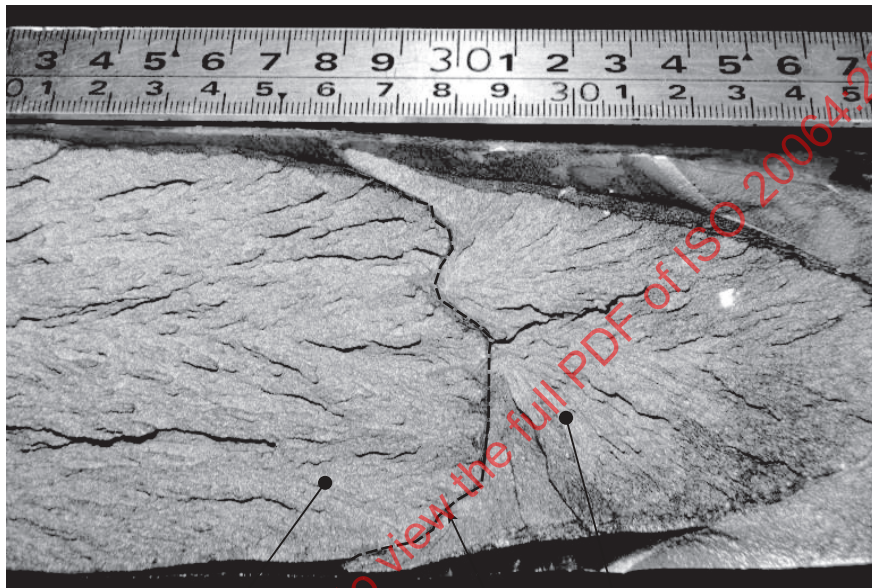
Key

- 1 brittle crack
- 2 ductile fracture resulting from tearing of the test piece after test
- 3 brittle crack initiation point
- 4 brittle crack arrest point

Figure 12 — Photographs of fracture surfaces and crack propagation path



a) Entire fracture surface



b) Enlarged view of arrest/re-initiation zone

Key

- 1 arrested crack
- 2 stretch zone
- 3 re-initiated crack

Figure 13 — Examples of re-initiated crack

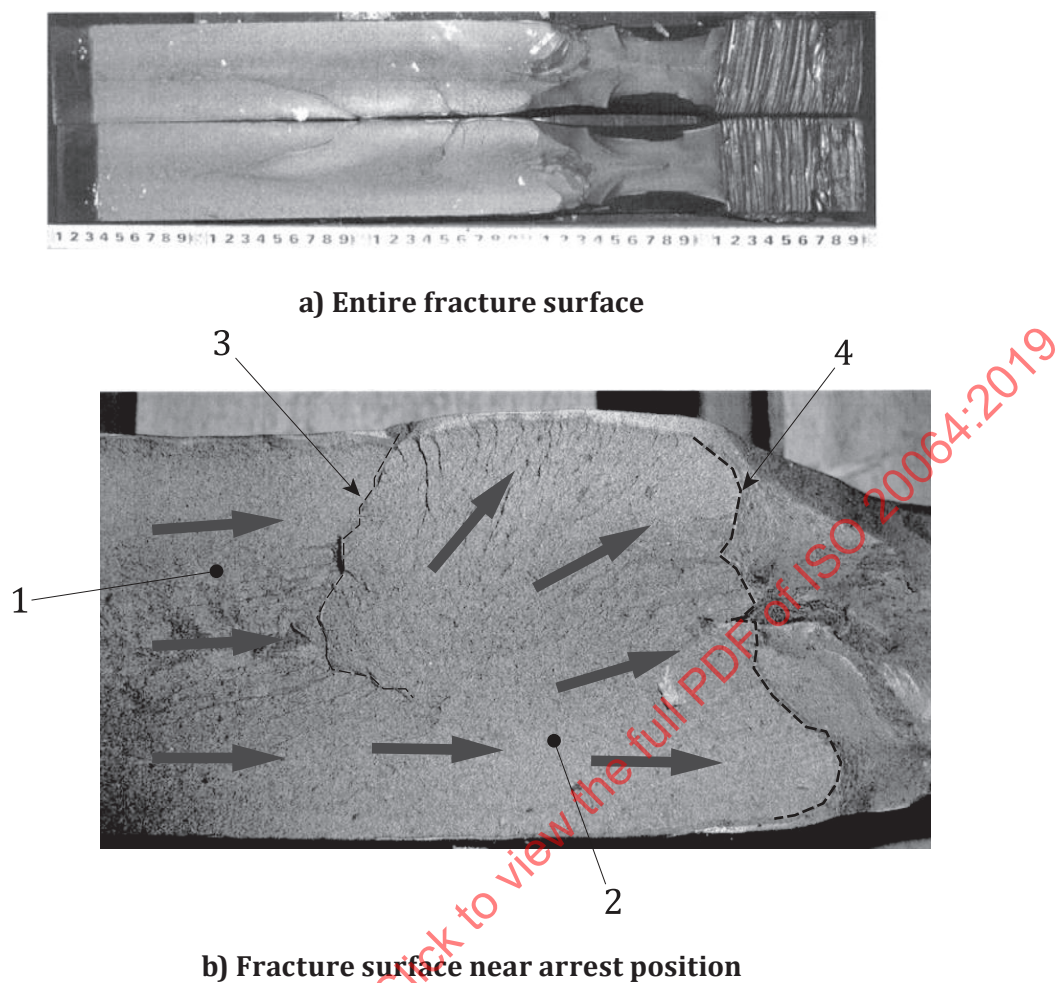
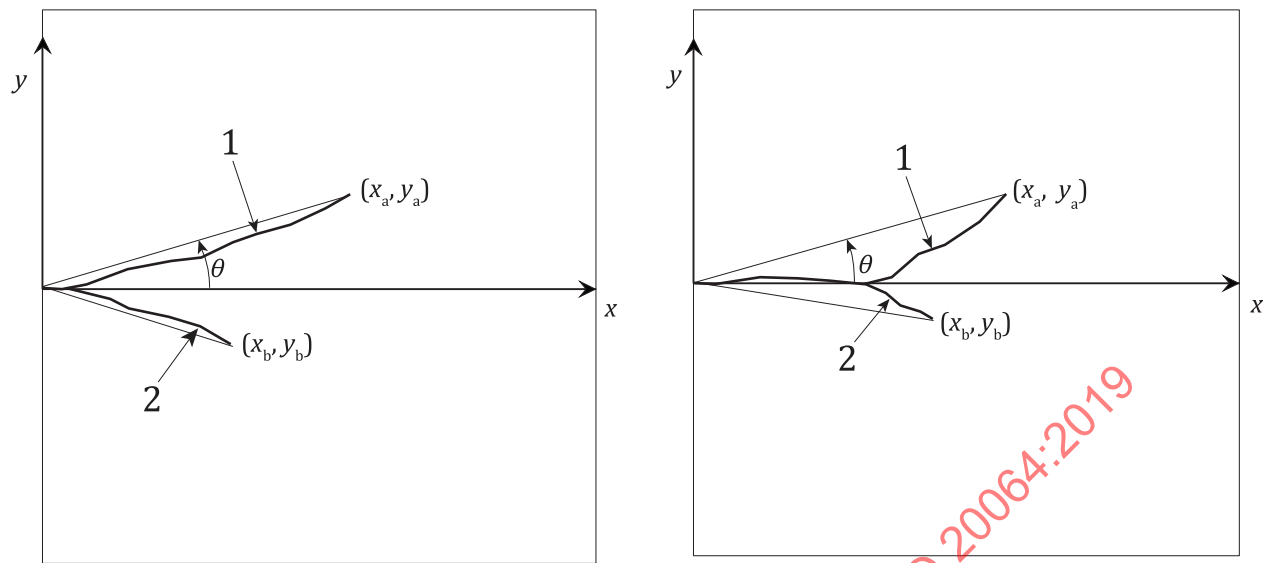


Figure 14 — Example of arrest after continuous propagation of crack partially in thickness direction

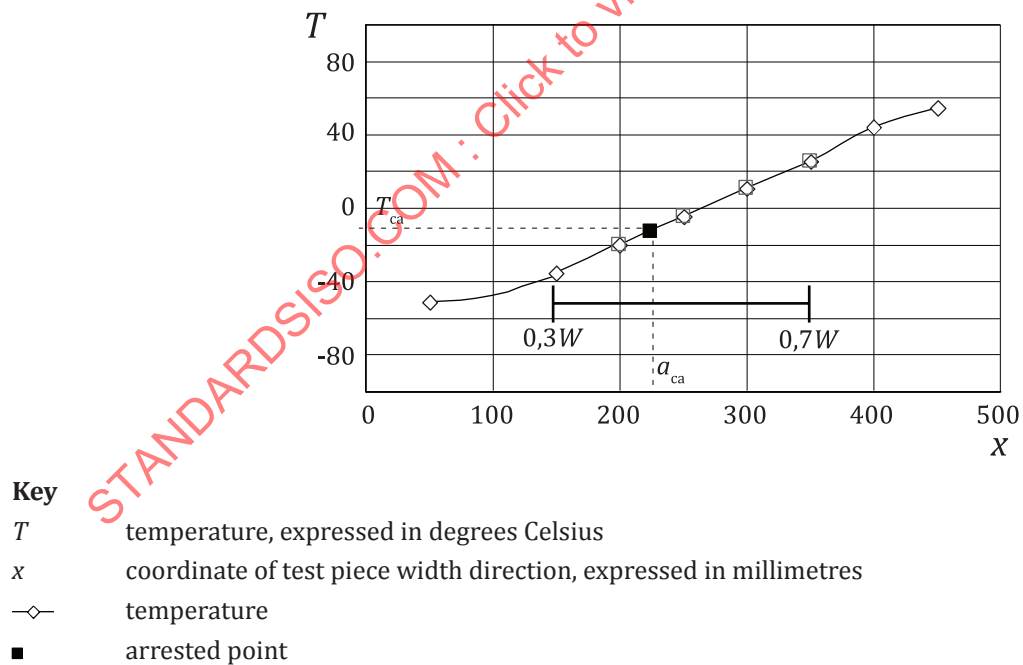


a) Case of branching from notch

b) Case of branching during brittle crack propagation

Key

- 1 main crack
- 2 branching crack

Figure 15 — Measurement methods of main crack and branch crack lengths**Key**

- T temperature, expressed in degrees Celsius
- x coordinate of test piece width direction, expressed in millimetres
- ◇— temperature
- arrested point

Figure 16 — Example of temperature distribution curve

9 Determination of arrest toughness

9.1 Validation of arrested crack

When an arrested crack satisfies all the conditions, a) to d), shown below, the length of the arrested crack determined by 8.4 is valid. If any of the conditions is not met, the arrest toughness calculated from 9.3 is invalid.

a) Conditions for crack propagation path

The crack path from crack initiation to arrest shall be within the range shown in Figure 17 because temperature is not controlled outside this range and crack deviation immediately after crack initiation leads to significant error in calculating stress intensity factor. However, in the case where a main crack tip lies within this range but a part of the main crack propagates outside the range, the arrest toughness is assessed as valid if the temperature at the most deviated position of the main crack in the y direction is lower than that at $y = 0$, and also K for the main crack is within $\pm 5\%$ of K for a straight crack of the same arrest crack length. The calculation of K for the main and the straight crack shall be as specified in Annex C.

b) Conditions for arrest crack length [see Formulae (5), (6) and (7)]

$$0,3 \leq \left(\frac{a_{ca}}{W} \right) \leq 0,7 \quad (5)$$

$$\left(\frac{a_{ca}}{B} \right) \geq 1,5 \quad (6)$$

$$\left(\frac{a_{ca}}{L_p} \right) \leq 0,15 \quad (7)$$

NOTE 1 Formula (5) is specified because the temperature gradient is controlled within $0,3W$ to $0,7W$ in the test piece width direction and also because too short a crack arrest can be influenced by impact loading [12][13][14].

NOTE 2 Formula (6) is specified because too short a crack as compared with the test piece thickness can lose two-dimensional crack assumption, possibly due to crack tunnelling. The validity of Formula (6) was checked for a 205 mm thick plate, in which a consistent crack arrest toughness value was obtained for (a_{ca}/B) ratio down to 1,5 [15].

NOTE 3 Formula (7) ensures a minimal influence of force drop at the centre of the test piece which can be caused by crack propagation and reflection of the stress wave at the two ends of the integrated test piece [11][12][13].

c) Conditions for crack straightness [see Formula (8)]

$$|y_a| \leq 50 \text{ mm} \quad (8)$$

In the case where $50 \text{ mm} < |y_a| \leq 100 \text{ mm}$ and $|\theta| \leq 30^\circ$, the result is valid only when the temperature at $x = 0,5W$ and $y = \pm 100 \text{ mm}$ falls within $\pm 2,5^\circ\text{C}$ of that at $x = 0,5W$ and $y = 0$.

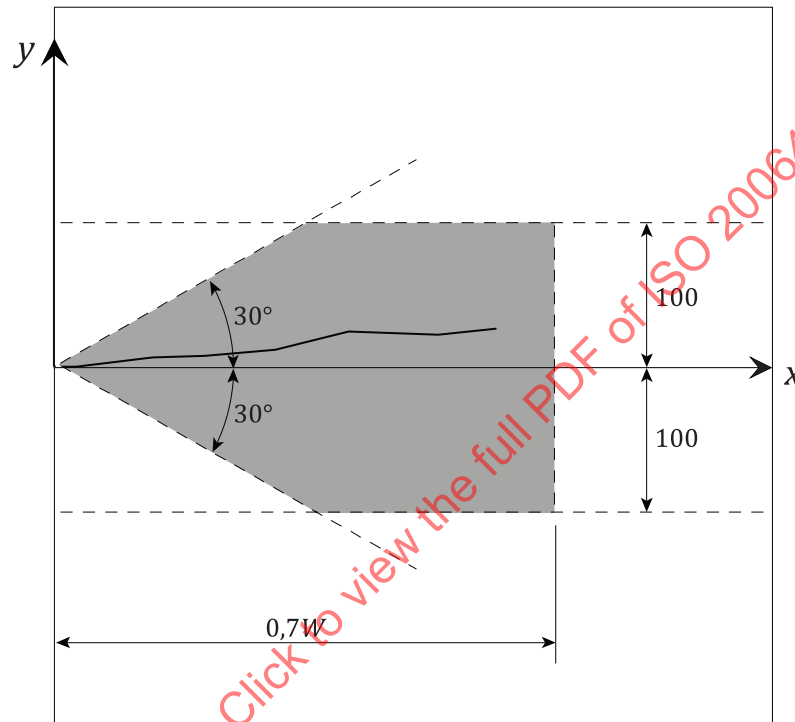
NOTE 4 If these conditions on arrest crack position are met, deviation of the stress intensity factor is less than 6 % from that of the straight crack with the same projected crack length [15].

d) Conditions for crack branching

$$\left(\frac{x_{br}}{x_a} \right) \leq 0,6 \quad (9)$$

NOTE 5 Deviation of the stress intensity factor for a crack with a branched crack is less than 5 % from that of the straight crack with the same projected crack length if [Formula \(9\)](#) is met^[15].

Dimensions in millimetres



Key

- x coordinate of test piece width direction, expressed in millimetres
 y coordinate of test piece longitudinal direction, expressed in millimetres

Figure 17 — Allowable range of main crack propagation path

9.2 Assessment of impact energy

9.2.1 General

The impact energy shall satisfy [Formula \(10\)](#). If it does not satisfy the formula, the value of arrest toughness calculated from the formulae in [9.3](#) is invalid:

$$\frac{E_i}{E_s + E_t} \leq \frac{5a_{ca} - 1\,050 + 1,4W}{0,7W - 150} \text{ and } 0,3 \leq \left(\frac{a_{ca}}{W} \right) \leq 0,7 \quad (10)$$

where

E_i is the impact energy calculated from [Formula \(1\)](#)

E_s and E_t the sum of which is the **elastic strain energy stored in the integrated test piece**, are calculated from [Formulae \(11\)](#) and [\(12\)](#), respectively.

NOTE Formula (10) has been established from a series of dynamic finite-element crack propagation analyses. The stress intensity factor comprises that for applied force and that for impact force. In calculating crack arrest toughness, only the former is considered in [Formulae \(13\)](#) and [\(14\)](#). If the impact energy is too high or the arrest crack length is too short, the influence of impact on the stress intensity factor is too large to be ignored. If [Formula \(10\)](#) is satisfied, the influence of impact on the stress intensity factor is low enough to obtain consistent crack arrest toughness^{[12][13][14]}.

$$E_s = \frac{10^9 F^2}{2E} \frac{L}{WB} \quad (11)$$

$$E_t = \frac{10^9 F^2}{E} \left(\frac{L_{ex}}{W_{ex} B_{ex}} + \frac{L_{tb}}{W_{tb} B_{tb}} \right) \quad (12)$$

9.2.2 In the case where the extension plates are multistage, as shown in [Figure 8 b\)](#), calculate and sum the strain energy of each extension plate using [Formula \(11\)](#).

9.2.3 In the case where extension plate widths are tapered as shown in [Figure 8 \(d\)](#), calculate the strain energy based on elastostatics.

9.3 Calculation of arrest toughness

The arrest toughness, K_{ca} , at the temperature, T_{ca} , shall be calculated from [Formula \(13\)](#) or [\(14\)](#) using the arrest crack length, a_{ca} , and the applied stress, σ , validated as described in [9.1](#). Calculate σ from [Formula \(15\)](#), where the applied force, F , is determined in accordance with [8.1.6](#) and [8.2.1](#).

$$K_{ca} [\text{MPa m}^{1/2}] = 0,031\ 6 \sigma \sqrt{\pi a_{ca}} \left[\frac{2W}{\pi a_{ca}} \tan \left(\frac{\pi a_{ca}}{2W} \right) \right]^{1/2} \quad (13)$$

$$K_{ca} [\text{N mm}^{-3/2}] = \sigma \sqrt{\pi a_{ca}} \left[\frac{2W}{\pi a_{ca}} \tan \left(\frac{\pi a_{ca}}{2W} \right) \right]^{1/2} \quad (14)$$

$$\sigma = \frac{10^6 F}{WB} \quad (15)$$

If the conditions specified in [9.1](#) and [9.2](#) are not satisfied, K_{ca} calculated from [Formula \(13\)](#) or [\(14\)](#) is invalid.

NOTE [Formulae \(13\)](#) and [\(14\)](#) provide the value of stress intensity factor for a dynamically propagating, decelerating and arrested crack by dynamic finite-element analyses.^[11] Other studies support these formulae for evaluating arrest toughness^{[4][5]}.

10 Reporting

[Table 4](#), which lists the following items, can be used for reporting the test result.

- Test material: steel type and yield stress at room temperature.
- Testing machine: capacity of the testing machine and force application and holding method.
- Test piece dimensions: thickness, width, length, angular distortion, and linear misalignment.
- Integrated test piece dimensions: extension plate thickness, extension plate width, integrated test piece length including the extension plates, and distance between the loading pins.

- e) Test conditions: applied force, applied stress, temperature gradient, impact energy, and ratio of impact energy to strain energy stored in the integrated test piece (sum of test piece strain energy and extension plate strain energy).
- f) Test results:
- 1) validation of arrest: crack length, presence or absence of crack branching, ratio of branch crack length to main crack, main crack angle, presence or absence of crack re-initiation, and arrest temperature;
 - 2) arrest toughness value.
- g) Temperature distribution at impact: thermocouple position, temperature value, and temperature distribution (see [Figure 16](#)).
- h) Test piece photographs: crack propagation path (top face) and fracture surfaces (both surfaces) (see [Figure 12](#)).
- i) Dynamic measurement results: history of crack propagation velocity, and strain change at tab plates (see [Annex F](#)).

NOTE i) is optional.

Table 4 — Report sheet for brittle crack arrest toughness test results

Item	Details	Symbol	Condi- tions/ results	Unit	Valid/ invalid
a) Test material	Steel type	—		—	—
	Yield stress at room temperature	R_p		MPa	—
b) Testing machine	Testing machine capacity	—		MN	—
	Force application and holding method				
c) Test piece dimensions	Thickness	B		mm	
	Width	W		mm	
	Length	L		mm	
	Angular distortion and linear mis-alignment	—		mm/m	
d) Integrated test piece dimensions	Extension plate thickness	B_{ex}		mm	
	Extension plate width	W_{ex}		mm	
	Test piece length including extension plate	$L + L_{ex}$		mm	
	Distance between loading pins	L_p		mm	
e) Test conditions	Applied force	F		MN	
	Applied stress	σ		MPa	
	Temperature gradient	—		°C/mm	
	Impact energy	E_i		J	
	Ratio of impact energy to strain energy stored in integrated test piece	$E_i/(E_s+E_t)$		—	

Table 4 (continued)

Item	Details		Symbol	Condi- tions/ results	Unit	Valid/ invalid
f) Test results	f) 1) Validation of crack propa- gation /arrest	Arrest crack length	a_{ca}		mm	
		Presence/absence of crack branching	—		—	—
		Ratio of branch crack length to main crack	x_{br}/x_a		—	
		Main crack angle	θ		degree (°)	
		Presence/absence of crack re-initiation	—		—	
		Arrest temperature	T_{ca}		°C	
	f) 2) Arrest toughness value		K_{ca}		MPa m ^{1/2} (N/mm ^{3/2})	
g) Temperature distribution at impact	Temperature measurement position		—	Attached	—	—
	Temperature at each temperature measurement position		—	Attached	°C	—
	Temperature distribution curve		—	Attached	—	
h) Test piece photographs	Crack propagation path		—	Attached	—	
	Fracture surfaces (both surfaces)		—	Attached	—	
i) Dynamic measurement results	History of crack propagation velocity		—	Attached	—	
	Strain change at tab plates		—	Attached	—	

Figure 18 shows an example of measured arrest toughness^[15]. Numbers in parentheses are applied stress to yield stress ratios. The open circle plot point is an invalid data point, which does not satisfy Formula (4).

If arrest toughness at a specific temperature is to be determined, the method described in Annex B shall be used.

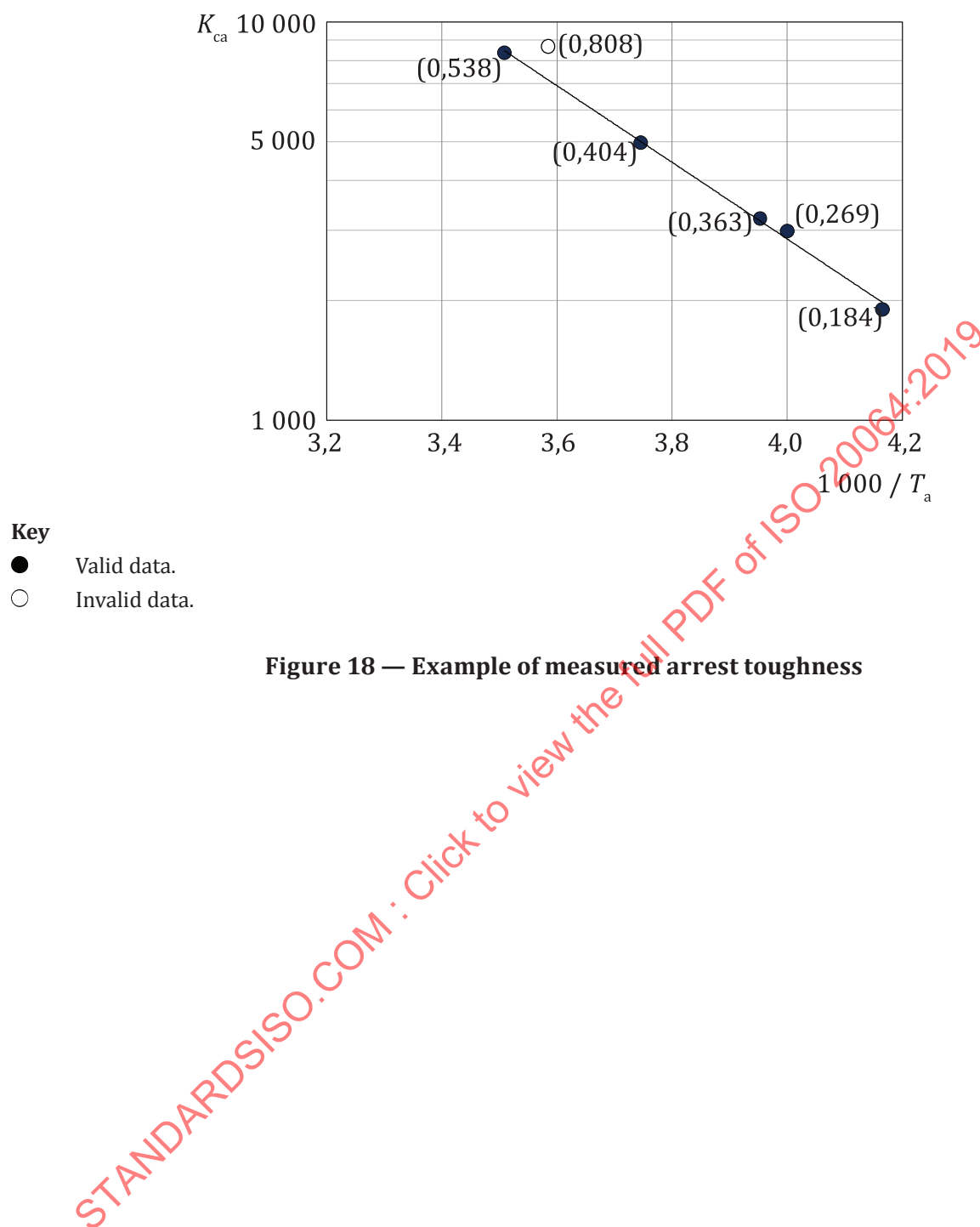


Figure 18 — Example of measured arrest toughness

Annex A **(informative)**

Devices and method for controlling and monitoring the temperature of test pieces

A.1 General

As specified in [7.1.1](#), the temperature gradient should be established in the test piece. This annex introduces recommended devices and a method for cooling and heating of a test piece.

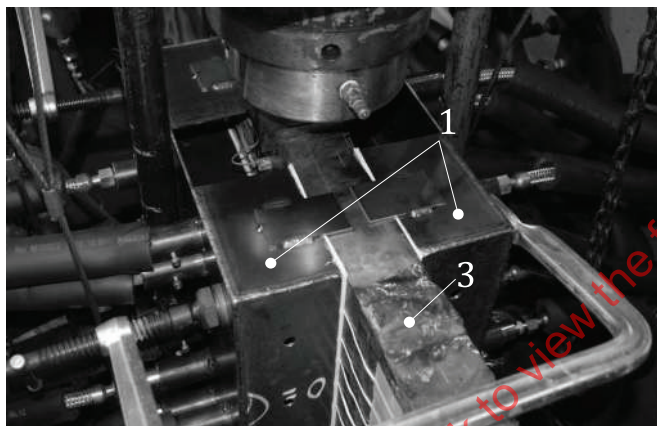
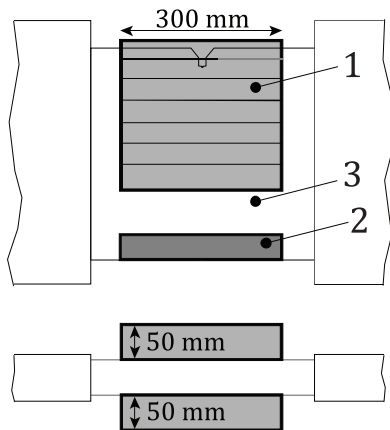
A.2 Devices and method

A.2.1 A cooling bath or a heating bath is mounted on the front and back faces of the test piece. The area around the crack initiation zone normally needs to be controlled to a temperature lower than room temperature, and hence requires cooling. Conversely, the opposite edge may be heated.

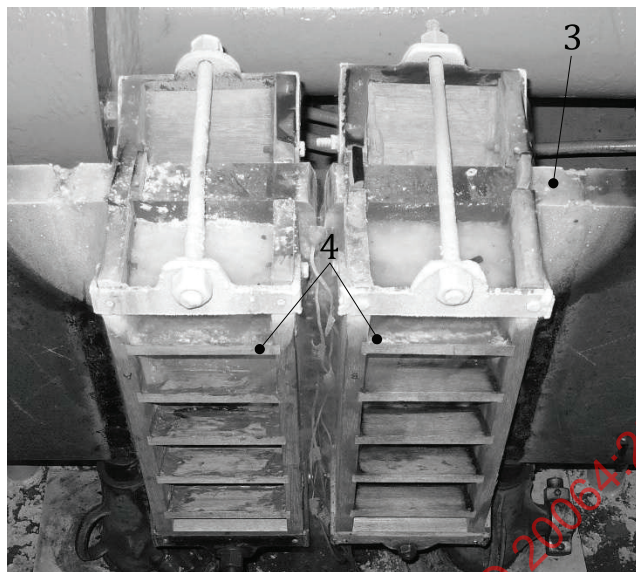
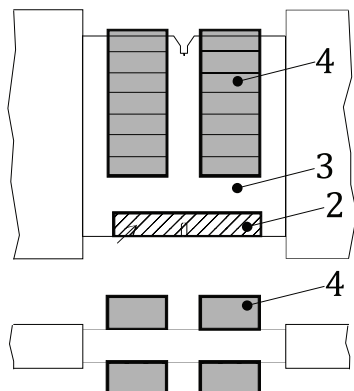
A.2.2 The cooling and heating baths generally have a box shape as shown in [Figure A.1](#) and should have sufficient capacity to control the temperature of the test piece. To avoid crack deviation due to non-uniform temperature distribution, bath lengths of 300 mm in the loading direction are recommended. [Figure A.1](#) a) and [Figure A.1](#) b) show examples of a direct spraying system and a side-bath system, respectively.

A.2.3 The most commonly used method of cooling is to spray liquid nitrogen on the test piece. A liquid such as alcohol may be used as a coolant to shorten the cooling time and to reduce temperature variation. Dry ice or liquid nitrogen can be used to cool liquid coolants. When using a liquid, the seal between the cooling bath and the test piece should be designed to avoid leakage.

A.2.4 Heating is generally applied using a liquid such as water as a medium. Integrated test pieces can be directly heated using a gas burner or an electrical heating device such as a strip heater.



a) Direct spray system



b) Side bath system

Key

- 1 cooling box (with spray system)
- 2 heating device (electric heater or water bath)
- 3 test piece
- 4 cooling box (side-bath)

Figure A.1 — Examples of cooling device

Annex B (normative)

Method for obtaining K_{ca} at a specific temperature

B.1 General

Because an arrest temperature cannot be determined beforehand in the test specified in the main part of this document, it is impossible to determine K_{ca} at a specific temperature, for example the design temperature of a structure, from a single test. This annex specifies a method for estimating K_{ca} at a specific temperature, T_D , from multiple tests in accordance with the main part of this document.

B.2 Method

B.2.1 A number of experimental data show a dependency of K_{ca} on arrest temperature, as expressed by [Formula \(B.1\)](#), where T_{caK} [K] ($=T_{ca}$ [°C] + 273), c and K_0 are constants^[16]:

$$K_{ca} = K_0 \exp\left(-\frac{c}{T_{caK}}\right) \quad (B.1)$$

The arrest toughness at a specific temperature T_D [K] should be obtained by following the procedures below. However, an alternative to [Formula \(B.1\)](#) may be used; see for example Reference ^[17].

B.2.2 Conduct multiple tests in accordance with the main part of this document to obtain at least four valid K_{ca} data. In the tests, combinations of applied force and temperature distribution are changed to obtain K_{ca} at different arrest temperatures. T_D should be located between the maximum and minimum of the arrest temperatures. If T_D is not located in this range, conduct additional tests to satisfy this condition.

B.2.3 Approximating $\log K_{ca}$ by a linear expression of $1/T_{caK}$, determine the coefficients $\log K_0$ and c for the data described in [B.2.2](#) by using a regression analysis, such as the least square method [see [Formula \(B.2\)](#)].

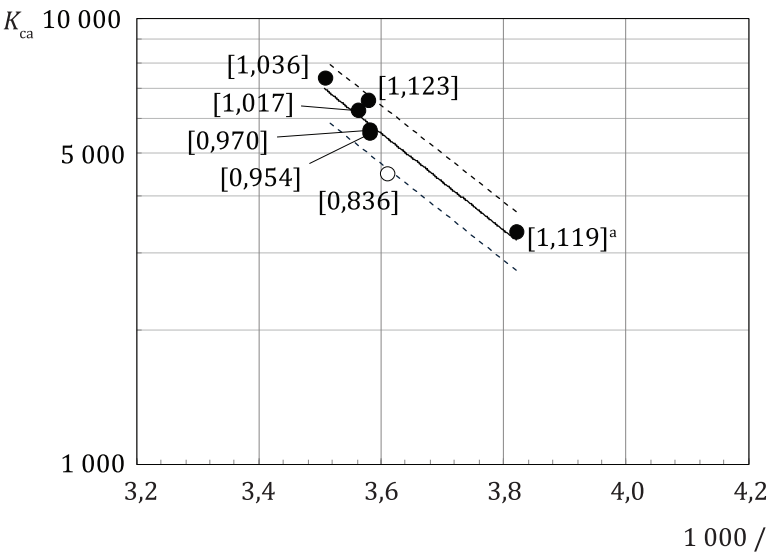
$$\log K_{ca} = \log K_0 - c \frac{1}{T_{caK}} \quad (B.2)$$

B.2.4 Obtain the value $(K_{ca}/K_0) \exp(-c/T_{caK})$ for each data point. When the number of data points outside the range of 0,85 to 1,15 does not exceed n , the regression analysis in [B.2.3](#) is considered valid. Here n is an integer obtained by rounding down the value of the number of data points divided by 6. If this condition is not met, conduct additional tests to add at least two data points and apply the procedure in [B.2.3](#) to the data.

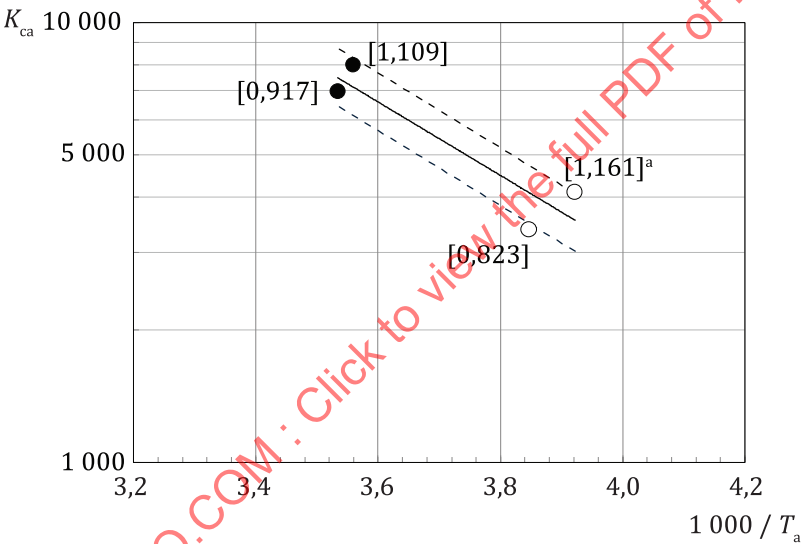
NOTE Validity range 0,85 to 1,15 is empirically determined^[10].

B.2.5 The value of $K_0 \exp(-c/T_D)$ is defined as the estimated value of K_{ca} at T_D . The estimated value for the temperature corresponding to a specific value of K_{ca} can be obtained from $T_{caK} = -c/\log(K_{ca}/K_0)$. If the condition specified in paragraph [B.2.4](#) is met, the estimated values are valid. Otherwise, they are invalid because they can have large uncertainty.

[Figure B.1 a\)](#) and [Figure B.1 b\)](#) show examples of valid and invalid estimations, respectively, of K_{ca} at specific temperature^[15]. Numbers in the brackets are the values of $(K_{ca}/K_0) \exp(-c/T_{caK})$, solid marked points have values between 0,85 and 1,15, and open marked points are outside this range.



a) Valid fitting



b) Invalid fitting

- Key**
- Data within $\pm 15\%$ bound from average line.
 - Data outside of $\pm 15\%$ bound from average line.
 - ^a Ratio of experimental K_{ca} value to that of [Formula \(B.2\)](#).

Figure B.1 — Examples of estimation for arrest toughness at specific temperature

Annex C (normative)

Calculation of stress intensity factors for a curved crack

C.1 General

This annex specifies the calculation method of K , which is necessary for the validation described in 9.1 a).

C.2 Method

K shall be calculated using finite element analysis or other methods with the same or a better accuracy. Static linear elastic plane stress is assumed. Before calculating K , make a preliminary calculation for a test piece with a known solution of K for a straight crack, and check that the deviation of K is 1 % of the known K or less^[19].

Assume that the test piece width is W and the length is $8W$ or more. Use a crack shape reproducing the crack shape of the test piece with an accuracy of ± 2 mm. Place singular elements at the crack tip. For comparison, also calculate the case of a straight crack (transverse to the applied stress direction) with the same projection length.

Apply uniform stresses to both ends of the test piece, calculate K for mode-I and mode-II for the crack of the test piece concerned, and obtain an equivalent K value from [Formula \(C.1\)](#)^[15]:

$$K = K_I \cos^3 \left(\frac{\varphi}{2} \right) + 3K_{II} \cos^2 \left(\frac{\varphi}{2} \right) \sin \left(\frac{\varphi}{2} \right) \quad (\text{C.1})$$

where φ is the angle normal to the applied stress at the main crack tip as shown in [Figure C.1](#), and the counter-clockwise angle from the x axis is defined as a positive angle. Attention shall also be given to the positive and negative of the value of K_{II} .

In the case of a straight crack, $K = K_I$ because $K_{II} = 0$ and $\varphi = 0$.

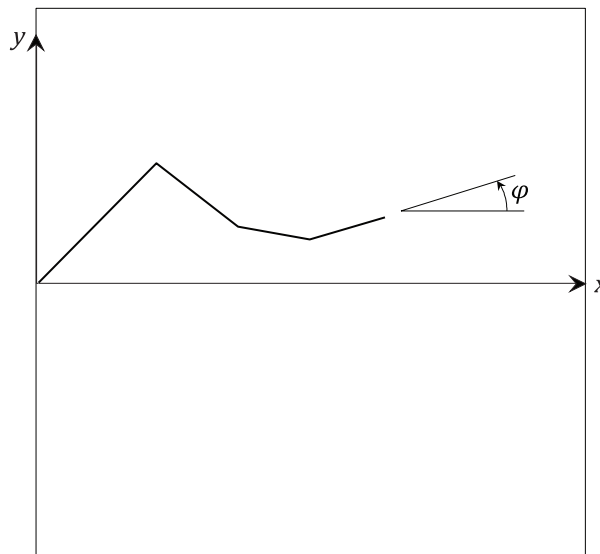


Figure C.1 — Definition of crack tip angle, φ , for a curved crack

Annex D (informative)

Double tension type arrest test

D.1 General

This annex describes a test method for a double tension type arrest test. This method differs from that of the main part of this document with respect to the crack initiation method only. The specifications described in the main part of this document should be applied to conditions not mentioned in this annex.

A double tension type arrest test piece consists of a main plate and a secondary loading tab. The main plate is a test plate for evaluating crack arrest toughness. The secondary loading tab is a crack starter plate for assisting a brittle crack to run into the main plate. After applying a predetermined applied force and a temperature gradient to the main plate, a secondary force is applied to the secondary loading tab by a secondary loading device to cause a brittle crack to initiate and run into the main plate. The arrest toughness is evaluated from the arrest temperature and the crack length in the main plate^{[1][14]}.

The narrow connection part between the main plate and the secondary loading tab in this test suppresses the flow of the tensile stress of the secondary loading tab into the main plate. The values of arrest toughness obtained by this method are considered equivalent to the results obtained by the test specified in the main part of this document.

D.2 Test piece configurations

Some recommended configurations of the double tension type arrest test piece and the secondary loading tab are shown in [Figures D.1](#) and [D.2](#), respectively. Subclause [6.2](#) applies to the configurations of the extension plates and tab plates.

Side-grooves and electron beam weld run may be used for a smooth entry of the crack into the main plate, unless these actions affect stress distribution in the main plate ^[20].

D.3 Temperature conditions and temperature control methods

Establish a temperature gradient in the main plate in order to evaluate its brittle crack arrest toughness. The specifications for temperature gradients and methods for establishing the temperature gradient are described in [Clause 7](#). In addition, in the double tension type arrest test, the secondary loading tab should be cooled without affecting the temperature gradient of the main plate. As in the cooling method for test pieces described in the main part of this document, cooling may be applied using a cooling box and a coolant. The cooling box of the secondary loading tab should be separated and independent of those of the main plate. The temperature of the secondary loading tab is measured using thermocouples as described in the main part of this document.

D.4 Secondary loading method

D.4.1 General

A secondary loading device is used to apply force to the secondary loading tab. The secondary loading device should satisfy the conditions given below.

D.4.2 Holding methods of secondary loading device

To avoid applying unnecessary force to the integrated test piece, the secondary loading device should be held in an appropriate way. Suspension-type or floor-type holding methods may be used. In the suspension-type method, the secondary loading device is suspended and held by a crane or a similar device. In the floor-type method, the secondary loading device is lifted and held by a frame or a similar device.

D.4.3 Loading system

A force or displacement control system may be used for applying force to the secondary loading tab. However, a hydraulic-type loading system is recommended.

D.4.4 Loading method

A pin-type loading method is recommended for loading the secondary load tab, but other methods may be used. The loading rate is not specified because it does not have a direct influence on the crack arrest behaviour of the main plate.

Dimensions in millimetres

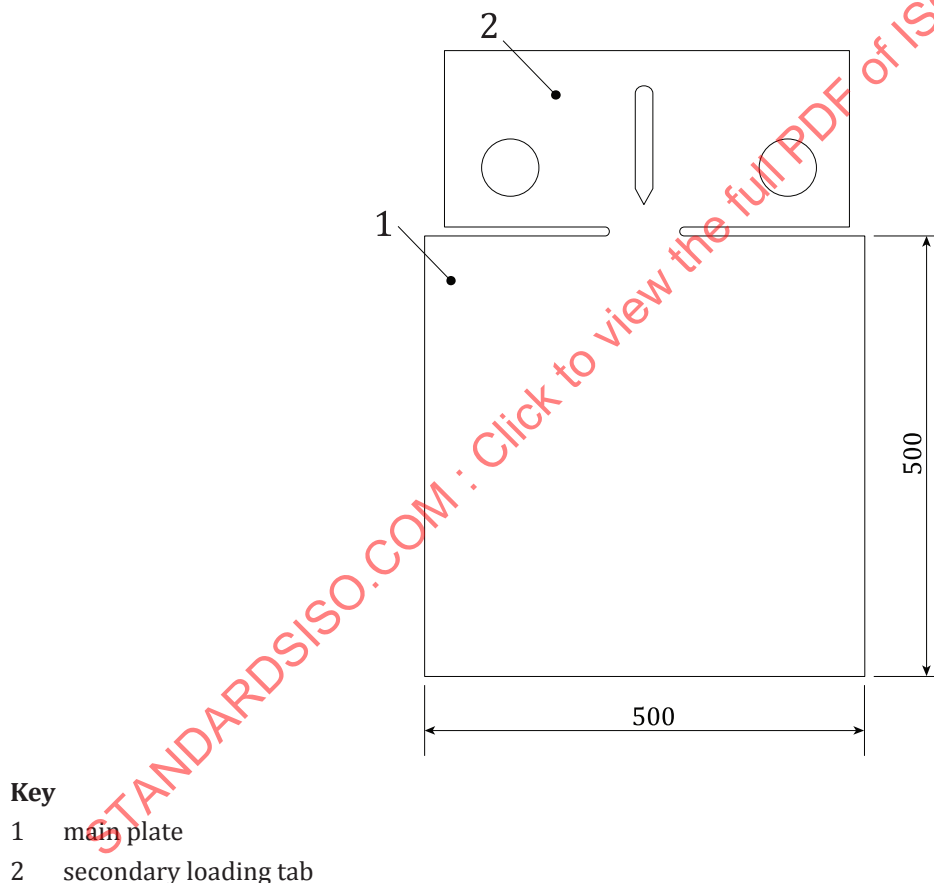


Figure D.1 — Example of test piece configuration with secondary loading tab