# W31 YP47 Steels and Brittle Crack Arrest Steels

(Jan 2013) (Rev.1 Sept 2015) (Rev.2 Dec 2019 Complete Revision)

## 1. Scope

### 1.1 General

1.1.1 This UR defines the requirements on YP47 steels and brittle crack arrest steels as required by UR S33.

1.1.2 Unless otherwise specified in this UR, UR W11 is to be followed.

### 1.2 YP47 steels

1.2.1 Steels designated as YP47 refer to steels with a specified minimum yield point of 460 $N/mm^2$.

1.2.2 The YP47 steels can be applied to longitudinal structural members in the upper deck region of container carriers (such as hatch side coaming, hatch coaming top and the attached longitudinals, etc.). Special consideration is to be given to the application of YP47 steels for other hull structures.

1.2.3 This UR gives the requirements for YP47 steels in thickness greater than 50mm and not greater than 100mm intended for the upper deck region of container carriers. For YP47 steels outside scope of the said thickness range, special consideration is to be given by the Classification Society.

### 1.3 Brittle crack arrest steels

1.3.1 The brittle crack designation can be assigned to YP36 and YP40 steels specified in UR W11 and YP47 steels specified in this UR, which meet the additional brittle crack arrest requirements and properties defined in this UR.

1.3.2 The application of brittle crack arrest steels is to comply with UR S33, which covers longitudinal structural members in the upper deck region of container carriers (such as hatch side coaming, upper deck, hatch coaming top and the attached longitudinals, etc.).

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Notes:

1. This UR is to be applied by IACS Societies to ships contracted for construction on or after 1 January 2014.

2. Revision 1 of this UR is to be applied by IACS Societies to ships contracted for construction on or after 1 January 2017.

3. The “contracted for construction” date means the date on which the contract to build the vessel is signed between the prospective owner and the shipbuilder. For further details regarding the date of “contract for construction”, refer to IACS Procedural Requirement (PR) No. 29.

4. Revision 2 of this UR is to be uniformly implemented by IACS Societies on ships contracted for construction on or after 01 January 2021.

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1.3.3 The thickness range of brittle crack arrest steels is over 50mm and not greater than 100mm as specified in Table 3 of this UR.

## 2 Material specifications

### 2.1 YP47 steels

Material specifications for YP47 steels are specified in Table 1 and Table 2.

**Table 1 Chemical composition and deoxidation practice for YP47 steels without specified brittle crack arrest properties**

| Grade | EH47 |
|---|---|
| Deoxidation Practice | Killed and fine grain treated |
| Chemical Composition % (ladle samples)(6)(7) | |
| C max. | 0.18 |
| Mn | 0.90 – 2.00 |
| Si max. | 0.55 |
| P max. | 0.020 |
| S max. | 0.020 |
| Al (acid soluble min) | 0.015 (1)(2) |
| Nb | 0.02 – 0.05 (2)(3) |
| V | 0.05 – 0.10 (2)(3) |
| Ti max. | 0.02(3) |
| Cu max. | 0.35 |
| Cr max. | 0.25 |
| Ni max. | 1.0 |
| Mo max. | 0.08 |
| $C_{eq}$ max.(4) | 0.49 |
| $P_{cm}$ max.(5) | 0.22 |

Notes:

1. The total aluminium content may be determined instead of the acid soluble content. In such cases the total aluminium content is to be not less than 0.020%.
2. The steel is to contain aluminium, niobium, vanadium or other suitable grain refining elements, either singly or in any combination. When used singly the steel is to contain the specified minimum content of the grain refining element. When used in combination, the specified minimum content of a fine graining element is not applicable.
3. The total niobium, vanadium and titanium content is not to exceed 0.12%.
4. The carbon equivalent $C_{eq}$ value is to be calculated from the ladle analysis using the following formula:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}(\%)$$

5. Cold cracking susceptibility $P_{cm}$ value is to be calculated using the following formula:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B(\%)$$

6. Where additions of any other element have been made as part of the steelmaking practice subject to approval by the Classification Society, the content is to be indicated on product inspection certificate.
7. Variations in the specified chemical composition may be allowed subject to approval of Classification Society.

**W31**
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**Table 2 Conditions of supply, grade and mechanical properties for YP47 steels without specified brittle crack arrest properties (1)**

| Supply condition | Grade | Tensile test | | | Impact test | | | |
|---|---|---|---|---|---|---|---|---|
| | | Yield Strength ($N/mm^2$) min. | Tensile Strength ($N/mm^2$) | Elongation (%) min. | Test Temp. (°C) | Average Impact Energy (J) min. | | |
| | | | | | | 50 < t ≤ 70 | 70 < t ≤ 85 | 85 < t ≤ 100 |
| | | | | | | Longitudinal | Longitudinal | Longitudinal |
| TMCP(2) | EH47 | 460 | 570 - 720 | 17 | -40 | 53 | 64 | 75 |

t: thickness (mm)

Notes:
1. The additional requirements for YP47 steel with brittle crack arrest properties is specified in 2.2 of this UR.
2. Other conditions of supply are to be in accordance with the Classification Society's procedures.

## 2.2 Brittle crack arrest steels

2.2.1 Brittle crack arrest steels are defined as steel plate with the specified brittle crack arrest properties measured by either the brittle crack arrest toughness $K_{ca}$ or Crack Arrest Temperature (CAT).

2.2.2 In addition to the required mechanical properties of UR W11 for YP36 and YP40 and Table 2 of this UR for YP47, brittle crack arrest steels are to comply with the requirements specified in Table 3 and Table 4 of this UR.

2.2.3 The brittle crack arrest properties specified in Table 3 are to be evaluated for the products in accordance with the procedure approved by the Classification Society. Test specimens are to be taken from each piece (means "the rolled product from a single slab or ingot if this is rolled directly into plates" as defined in URW11), unless otherwise agreed by the Classification Society.

**Table 3 Requirement of brittle crack arrest properties for brittle crack arrest steels**

| Suffix to the steel grade(1) | Thickness range (mm) | Brittle crack arrest properties(2)(6) | |
|---|---|---|---|
| | | Brittle Crack Arrest Toughness $K_{ca}$ at -10 °C ($N/mm^{3/2}$) (3) | Crack Arrest Temperature CAT (°C) (4) |
| BCA1 | 50 < t ≤ 100 | 6,000 min. | -10 or below |
| BCA2 | 80 < t ≤ 100(7) | 8,000 min. | (5) |

t: thickness (mm)

Notes:
1. Suffix "BCA1" or "BCA2" is to be affixed to the steel grade designation (e.g. EH40-BCA1, EH47-BCA1, EH47-BCA2, etc.).
2. Brittle crack arrest properties for brittle crack arrest steels are to be verified by either the brittle crack arrest toughness $K_{ca}$ or Crack Arrest Temperature (CAT).
3. $K_{ca}$ value is to be obtained by the brittle crack arrest test specified in Annex 3 of this UR.
4. CAT is to be obtained by the test method specified in Annex 4 of this UR.
5. Criterion of CAT for brittle crack arrest steels corresponding to Kca=8,000 $N/mm^{3/2}$ is to be approved by the Classification Society
6. Where small-scale alternative tests are used for product testing (batch release testing), these test methods are to be approved by the Classification Society.
7. Lower thicknesses may be approved at the discretion of the Classification Society.

**W31 (cont)** **Table 4** **Chemical composition and deoxidation practice for brittle crack arrest steels**

| Grade | EH36-BCA | EH40-BCA | EH47-BCA |
|---|---|---|---|
| Deoxidation Practice | Killed and fine grain treated | | |
| Chemical Composition % (1)(7)(8) (ladle samples) | | | |
| C max. | 0.18 | | 0.18 |
| Mn | 0.90 – 2.00 | | 0.90 – 2.00 |
| Si max. | 0.50 | | 0.55 |
| P max. | 0.020 | | 0.020 |
| S max. | 0.020 | | 0.020 |
| Al (acid soluble min) | 0.015 (2) (3) | | 0.015 (2) (3) |
| Nb | 0.02 – 0.05 (3) (4) | | 0.02 – 0.05 (3) (4) |
| V | 0.05 – 0.10 (3) (4) | | 0.05 – 0.10 (3) (4) |
| Ti max. | 0.02(4) | | 0.02(4) |
| Cu max. | 0.50 | | 0.50 |
| Cr max. | 0.25 | | 0.50 |
| Ni max. | 2.0 | | 2.0 |
| Mo max. | 0.08 | | 0.08 |
| $C_{eq}$ max.(5) | 0.47 | 0.49 | 0.55 |
| $P_{cm}$ max.(6) | - | | 0.24 |

Notes:

1. Chemical composition of brittle crack arrest steels shall comply with Table 4 of this UR, regardless of chemical composition specified in UR W11 and Table 1 of this UR.
2. The total aluminium content may be determined instead of the acid soluble content. In such cases the total aluminium content is to be not less than 0.020%.
3. The steel is to contain aluminium, niobium, vanadium or other suitable grain refining elements, either singly or in any combination. When used singly the steel is to contain the specified minimum content of the grain refining element. When used in combination, the specified minimum content of a fine graining element is not applicable.
4. The total niobium, vanadium and titanium content is not to exceed 0.12%.
5. The carbon equivalent $C_{eq}$ value is to be calculated from the ladle analysis using the following formula:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}(\%)$$

6. Cold cracking susceptibility $P_{cm}$ value is to be calculated using the following formula:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B(\%)$$

7. Where additions of any other element have been made as part of the steelmaking practice subject to approval by the Classification Society, the content is to be indicated on product inspection certificate.
8. Variations in the specified chemical composition may be allowed subject to approval of Classification Society.

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## 3 Manufacturing approval scheme

### 3.1 YP47 steels

Manufacturing approval scheme for YP47 steels is to be in accordance with Annex 1 of this UR.

### 3.2 Brittle crack arrest steels

Manufacturing approval scheme for brittle crack arrest steels is to be in accordance with Annex 2 of this UR.

## 4 Welding procedure qualification test

### 4.1 YP47 steels

4.1.1 General

Approval test items, test methods and acceptance criteria not specified in this UR are to be in accordance with the Classification Society's procedures.

4.1.2 Approval range

UR W28 is to be followed for approval range.

4.1.3 Impact test

UR W28 is to be followed for impact test. 64J at -20°C is to be satisfied.

4.1.4 Hardness

HV10, as defined in UR W28, is to be not more than 350. Measurement points are to include mid-thickness position in addition to the points required by UR W28.

4.1.5 Tensile test

Tensile strength in transverse tensile test is to be not less than 570N/mm$^2$.

4.1.6 Brittle fracture initiation test

Deep notch test or CTOD test may be required.

Test method and acceptance criteria are to be considered appropriate by the Classification Society.

### 4.2 Brittle crack arrest steels

4.2.1 General

Where Welding Procedure Specification (WPS) for the non-BCA steels has been approved by the Classification Society, the said WPS is applicable to the same welding procedure applied to the same grade with suffix "BCA1" or "BCA2" specified in Table 3 of this UR except high heat input processes over 50kJ/cm.

**W31 (cont)**

The requirements for welding procedure qualification test for brittle crack arrest steels is to be in accordance with the relevant requirements for each steel grade excluding suffix “BCA1” or “BCA2” specified in Table 3 of this UR, except for 4.2.2 below.

4.2.2 Hardness

For YP47 steels with brittle crack arrest properties, HV10, as defined in UR W28, is to be not more than 380. Measurement points are to include mid-thickness position in addition to the points required by UR W28.

## 5 Production welding

### 5.1 YP47 steels

5.1.1 Welder

Welders engaged in YP47 welding work are to possess welder’s qualifications specified in UR W32.

5.1.2 Short bead

Short bead length for tack and repairs of welds by welding are not to be less than 50mm.

In the case where $P_{cm}$ is less than or equal to 0.19, 25mm of short bead length may be adopted with approval of the Classification Society.

5.1.3 Preheating

Preheating is to be 50°C or over when air temperature is 5°C or below.

In the case where $P_{cm}$ is less than or equal to 0.19 and the air temperature is below 5°C but above 0°C, alternative preheating requirements may be adopted with approval of the Classification Society.

5.1.4 Welding consumable

Approval procedure, approval test items, test methods and acceptance criteria not specified in this UR are to be in accordance with UR W17.

Specifications of welding consumables for YP47 steel plates are to be in accordance with Table 5.

**Table 5 Mechanical properties for deposited metal tests for welding consumables**

| Mechanical Properties | | | Impact test | |
|---|---|---|---|---|
| Yield Strength ($N/mm^2$) min. | Tensile Strength ($N/mm^2$) | Elongation (%) min. | Test Temp. (°C) | Average Impact Energy (J) min. |
| 460 | 570 - 720 | 19 | -20 | 64 |

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Consumable tests for butt weld assemblies are to be in accordance with Table 6.

**Table 6 Mechanical properties for butt weld tests for welding consumables**

| Tensile strength ($N/mm^2$) | Bend test ratio: $\frac{D}{t}$ | Charpy V-notch impact tests | |
|---|---|---|---|
| | | Test temperature (°C) | Average absorbed energy (J) min. |
| 570 - 720 | 4 | - 20 | 64 |

5.1.5 Others

Special care is to be paid to the final welding so that harmful defects do not remain.

Jig mountings are to be completely removed with no defects in general, otherwise the treatment of the mounting is to be accepted by the Classification Society.

### 5.2 Brittle crack arrest steels

Welding work (such as relevant welder's qualification, short bead, preheating, selection of welding consumable, etc.) for brittle crack arrest steels is to be in accordance with the relevant requirements for each steel grade excluding suffix "BCA1" or "BCA2" specified in Table 3 of this UR.

**W31 (cont)**

# Annex 1 Manufacturing Approval Scheme for YP47 Steels

## 1. Scope

1.1 This Annex specifies, as given in 3.1 of this UR, the manufacturing approval scheme for YP47 steels of grade EH47.

1.2 Unless otherwise specified in this Annex, Appendix A2 of UR W11 is to be followed.

## 2. Approval tests

### 2.1 Extent of the approval tests

3.1 (c) and (d), Appendix A2 of UR W11 are not applied to manufacturing approval of YP47 steels.

### 2.2 Type of tests

2.2.1 Brittle fracture initiation test

Deep notch test or Crack Tip Opening Displacement (CTOD) test is to be carried out. Test method is to be in accordance with the Classification Society's practice.

2.2.2 Weldability test

(a) Y-groove weld cracking test (Hydrogen crack test)

The test method is to be in accordance with recognized national standards such as JIS Z 3158-2016 or CB/T 4364-2013. Acceptance criteria are to be in accordance with the Classification Society's practice.

(b) Brittle fracture initiation test

Deep notch test or CTOD test is to be carried out. Test method and results are to be considered appropriate by the Classification Society.

2.2.3 Other tests

In addition to the requirement specified in 2.2.1 and 2.2.2 above, the approval tests required for steels specified in Appendix A2 of UR W11 are to be carried out. Additional tests may be required when deemed necessary by the Classification Society.

**W31 (cont)**

## Annex 2 Manufacturing Approval Scheme for Brittle Crack Arrest Steels

### 1. Scope

1.1 This Annex specifies, as given in 3.2 of this UR, the manufacturing approval scheme for brittle crack arrest steels.

1.2 Unless otherwise specified in this Annex, Appendix A2 of UR W11 and/or Annex1 of this UR are to be followed.

### 2. Approval Application

#### 2.1 Documents to be submitted

The manufacturer is to submit to the Classification Society the following documents together with those required in 2.1, Appendix A2 of UR W11:

a) In-house test reports of the brittle crack arrest properties of the steels intended for approval
b) Approval test program for the brittle crack arrest properties (see 3.1 below)
c) Production test procedure for the brittle crack arrest properties.

### 3. Approval tests

#### 3.1 Extent of the approval tests

3.1.1 The extent of the test program is specified in 3.2, 3.3 and 3.4 of this Annex.
If the manufacturing process and mechanism to ensure the brittle crack arrest properties for the steels intended for approval are same, 3.1, Appendix A2 of UR W11 is to be followed for the extent of the approval tests.

3.1.2 The number of test samples and test specimens may be increased when deemed necessary by the Classification Society, based on the in-house test reports of the brittle crack arrest properties of the steels intended for approval specified in 2.1 a).

#### 3.2 Type of tests

3.2.1 Brittle crack arrest tests are to be carried out in accordance with 3.3 of this Annex in addition to the approval tests specified in Appendix A2 of UR W11 and/or Annex 1 of this UR.

3.2.2 In the case of applying for addition of the specified brittle crack arrest properties for YP36, YP40 and YP47 steels of which, manufacturing process has been approved by the Classification Society (i.e. The aim analyses, method of manufacture and condition of supply are similar and the steelmaking process, deoxidation and fine grain practice, casting method and condition of supply are the same), brittle crack arrest tests, chemical analyses, tensile test and Charpy V-notch impact test are to be carried out in accordance with Annex 2 of this UR and Appendix A2 of UR W11.

#### 3.3 Test specimens and testing procedure of brittle crack arrest tests

3.3.1 The test specimens of the brittle crack arrest tests are to be taken with their longitudinal axis parallel to the final rolling direction of the test plates.

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3.3.2 The loading direction of brittle crack tests is to be parallel to the final rolling direction of the test plates.

3.3.3 The thickness of the test specimens of the brittle crack arrest tests is to be the full thickness of the test plates.

3.3.4 The test specimens and repeat test specimens are to be taken from the same steel plate.

3.3.5 The thickness of the test specimen is to be the maximum thickness of the steel plate requested for approval.

3.3.6 In the case where the brittle crack arrest properties are evaluated by $K_{ca}$, the brittle crack arrest test method is to be in accordance with Annex 3 of this UR. In the case where the brittle crack arrest properties are evaluated by CAT, the test method is to be in accordance with Annex 4 of this UR.

### 3.4 Other tests

Additional tests may be required when deemed necessary by the Classification Society in addition to the tests specified in 3.3.

## 4. Results

Appendix A2 of UR W11 is to be followed for the results.

Additionally, results of test items and the procedures shall comply with the test program approved by the Classification Society. In the case where the brittle crack arrest properties are evaluated by $K_{ca}$ or CAT, the manufacturer also is to submit to the Classification Society the brittle crack arrest test reports in accordance with Annex 3 for Kca and Annex 4 for CAT of this UR.

## 5. Approval and Certification

Upon satisfactory completion of the survey and tests, approval is granted by the Classification Society with the grade designation having the suffix “BCA1” or “BCA2” (e.g. EH40-BCA1, EH47-BCA1, EH47-BCA2, etc.).

## 6. Renewal of approval

The manufacturer is also to submit to the Classification Society actual manufacturing records of the approved brittle crack arrest steels within the term of validity of the manufacturing approval certificate.

Note: Chemical composition, mechanical properties, brittle crack arrest properties (e.g. brittle crack arrest test results or small-scale alternative test results) and nominal thickness are to be described in the form of histogram or statistics.

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## Annex 3 Test Method for Brittle Crack Arrest Toughness, $K_{ca}$

Setting a temperature gradient in the width direction of a test specimen, and applying uniform stress to the test specimen, strike the test specimen to initiate a brittle crack from the mechanical notch at the side of the test specimen and causes crack arrest (temperature gradient type arrest testing). Using the stress intensity factor, calculate the brittle crack arrest toughness, $K_{ca}$, from the applied stress and the arrest crack length. This value is the brittle crack arrest toughness at the temperature of the point of crack arrest (arrest temperature). To obtain $K_{ca}$ at a specific temperature followed by the necessary evaluation, the method specified in Appendix A of this Annex 3 can be used.

As a method for initiating a brittle crack, a secondary loading mechanism can also be used (see Appendix B of this Annex 3 “Double tension type arrest test”).

### 1. Scope

This Annex 3 specifies the test method for brittle crack arrest toughness (i.e. $K_{ca}$) of steel using fracture mechanics parameter. This Annex 3 is applicable to hull structural steels with the thickness over 50mm and not greater than 100mm specified in UR W11 or this UR.

### 2. Symbols and their significance

The symbols and their significance used in this standard are shown in Table A3-1.

**Table A3-1 Symbols and their significance**

| Symbol | Unit | Significance |
|---|---|---|
| $a$ | mm | Crack length or arrest crack length |
| $E$ | $N/mm^2$ | Modulus of longitudinal elasticity |
| $E_i$ | J | Impact energy |
| $E_s$ | J | Strain energy stored in a test specimen |
| $E_t$ | J | Total strain energy stored in tab plates and pin chucks |
| $F$ | MN | Applied load |
| $K$ | $N/mm^{3/2}$ | Stress intensity factor |
| $K_{ca}$ | $N/mm^{3/2}$ | Arrest toughness |
| $L$ | mm | Test specimen length |
| $L_p$ | mm | Distance between the loading pins |
| $L_{pc}$ | mm | Pin chuck length |
| $L_{tb}$ | mm | Tab plate length |
| $T$ | °C | Temperature or arrest temperature |
| $t$ | mm | Test specimen thickness |

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**Table A3-1 Symbols and their significance (cont'd)**

| Symbol | Unit | Significance |
|---|---|---|
| $t_{tb}$ | mm | Tab plate thickness |
| $t_{pc}$ | mm | Pin chuck thickness |
| $W$ | mm | Test specimen width |
| $W_{tb}$ | mm | Tab plate width |
| $W_{pc}$ | mm | Pin chuck width |
| $x_a$ | mm | Coordinate of a 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 a main crack tip in the stress loading direction |
| $y_{br}$ | mm | Coordinate of the longest branch crack tip in the stress loading direction |
| $\sigma$ | N/mm$^2$ | Applied stress |
| $\sigma_{Y0}$ | N/mm$^2$ | Yield stress at room temperature |

## 3. Testing equipment

The following specifies the testing machine needed for conducting the brittle crack arrest test. Testing machine is used to apply tensile force to an integrated specimen, and impact equipment is used to generate a brittle crack on the test specimen.

### 3.1 Testing machine

3.1.1 Loading method

Tensile load to an integrated specimen shall be hydraulically applied.
The loading method to an integrated specimen using the testing machine shall be of a pin type. The stress distribution in the plate width direction shall be made uniform by aligning the centres of the loading pins of both sides and the neutral axis of the integrated specimen.

3.1.2 Loading directions

The loading directions shall be either vertical or horizontal. In the case of the horizontal direction, test specimen surfaces shall be placed either perpendicular to the ground.

3.1.3 Distance between the loading pins

The distance between the loading pins shall be approximately 3.4$W$ or more, where $W$ is the width of the test specimen. Since the distance between the loading pins sometimes has an effect on the load drop associated with crack propagation, the validity of the test results is determined by the judgment method described in 7.1.

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### 3.2 Impact equipment

3.2.1 Impact methods

Methods to apply an impact load to an integrated specimen shall be of a drop weight type or of an air gun type.

The wedge shall be hard enough to prevent significant plastic deformation caused by the impact. The wedge thickness shall be equal to or greater than that of the test specimen, and the wedge angle shall be greater than that of the notch formed in the test specimen and have a shape capable of opening up the notch of the test specimen.

## 4. Test specimens

### 4.1 Test specimen shapes

The standard test specimen shape is shown in Figure A3-1. Table A3-2 shows the ranges of test specimen thicknesses, widths and width-to-thickness ratios.

The test specimen length shall be, in principle, equal to or greater than its width.

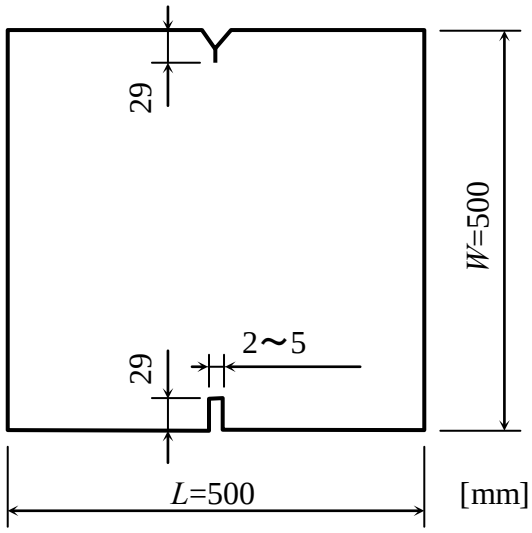


**Figure A3-1 Standard test specimen shape**

**Table A3-2 Dimensions of test specimens**

| | |
|---|---|
| Test specimen thickness, $t$ | 50 mm ≤ $t$ ≤ 100 mm |
| Test specimen width, $W$ | 350 mm ≤ $W$ ≤ 1000 mm<br>(Standard width: $W$ = 500 mm) |
| Test specimen width/test specimen thickness, $W/t$ | $W/t$ ≥ 5 |

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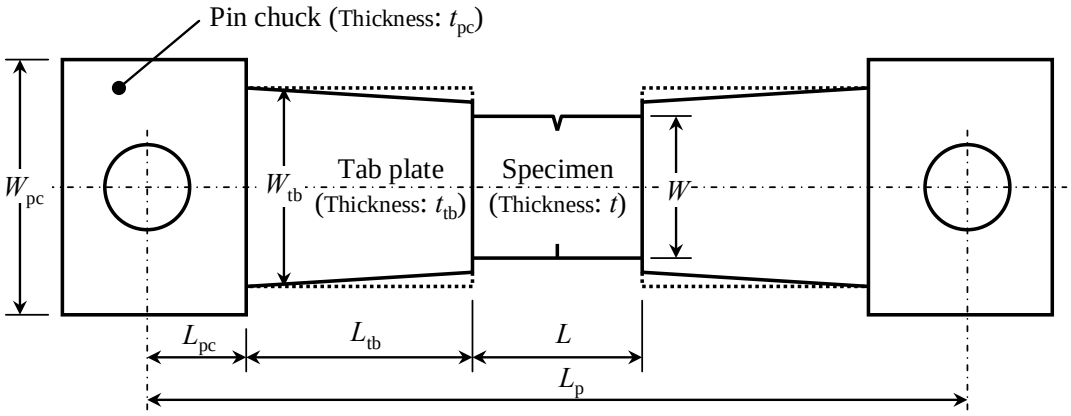
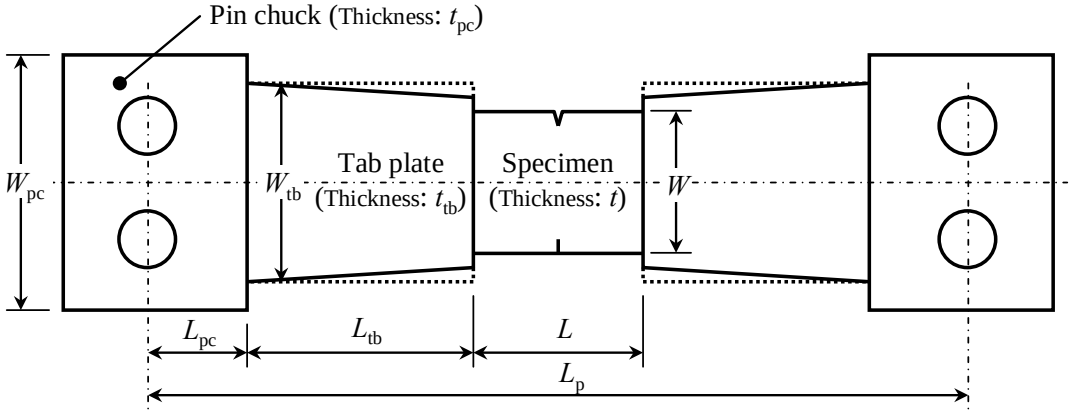
### 4.2 Shapes of tab plates and pin chucks

The definitions of the dimensions of the tab plates and pin chucks are shown in Figure A3-2. Typical examples are shown in Figure A3-3.

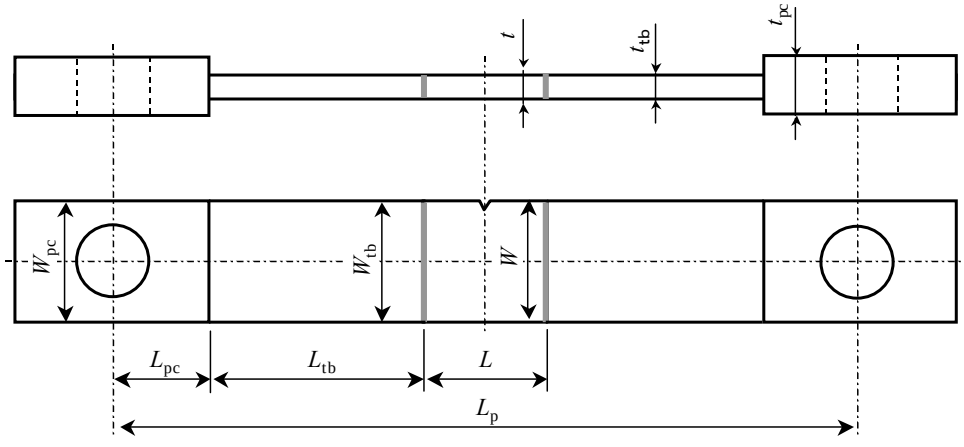



**(a) Single-pin type**




**(b) Double-pin type**

**Figure A3-2 Definitions of dimensions of tab plates and pin chucks**




**(a) Example 1**

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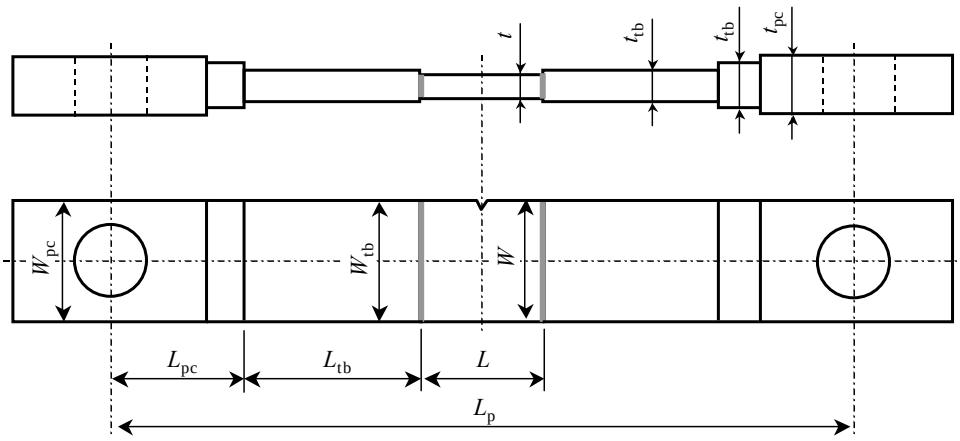
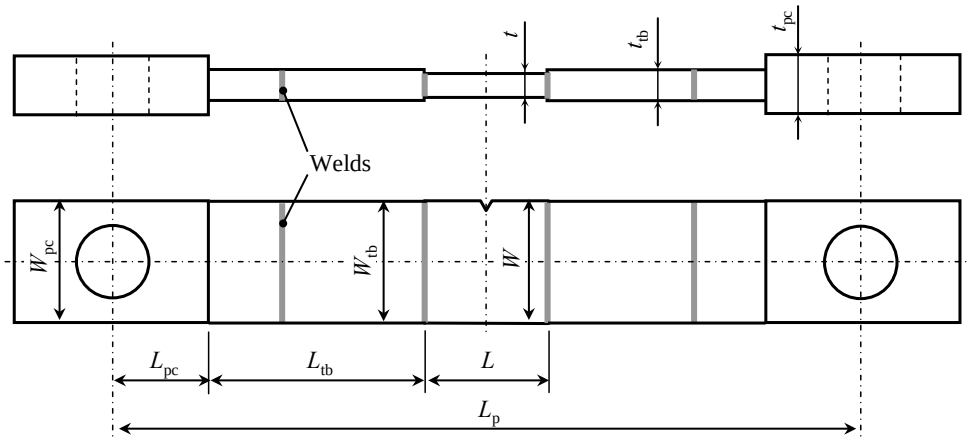



**(b) Example 2**




**(c) Example 3**

**Figure A3-3 Examples of the shapes of tab plates and pin chucks**

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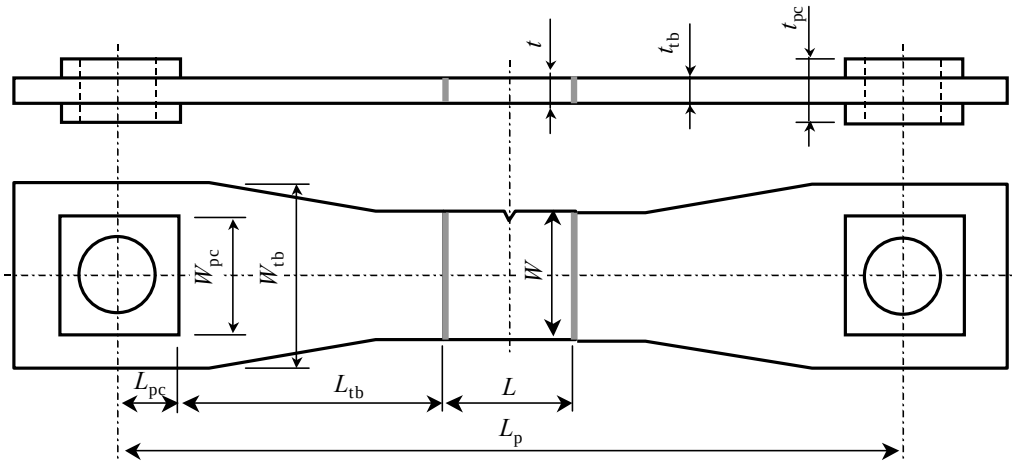
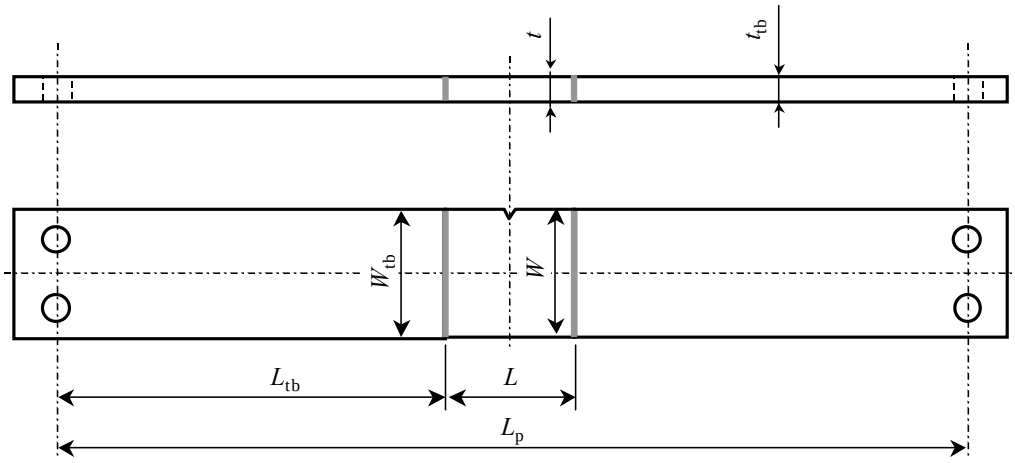



**(d) Example 4**




**(e) Example 5**

**Figure A3-3 Examples of shapes of tab plates and pin chucks (cont'd)**

4.2.1 Tab plates

The tolerances of tab plate dimensions are shown in Table A3-3. When the lengths of the tab plates attached to both ends of a test specimen are different, the shorter length shall be used as the tab length, $L_{tb}$.

**Table A3-3 Tolerances of tab plate dimensions**

| | |
|---|---|
| Tab plate thickness, $t_{tb}$ | $0.8t \le t_{tb} \le 1.5t$ |
| Tab plate width, $W_{tb}$ | $W \le W_{tb} \le 2.0W$ |
| Total length of a test specimen and tab plates, $L + 2L_{tb}$<br>(Total length of a test specimen and a single tab plate $L + L_{tb}$) | $L + 2L_{tb} \ge 3.0W$<br>($L + L_{tb} \ge 2.0W$) |
| Tab plate length ($L_t$)/Tab plate width, ($W$) | $L_{tb}/W \ge 1.0$ |

**W31**
**(cont)**

4.2.2 Pin chucks

The pin chuck width, $W_{pc}$, shall be in principle equal to or more than the tab plate width, $W_{tb}$.

The pin chucks shall be designed to have a sufficient load bearing strength. When pin chucks attached to both ends of an integrated specimen are asymmetric, the length of the shorter one shall be used as the pin chuck length, $L_{pc}$.

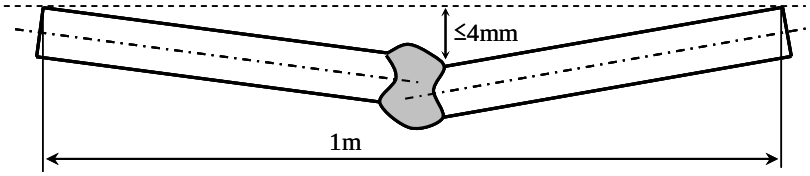
The distance between the pins, $L_p$, is obtained from the equation (1). In the case as shown in Figure A3-3 (e), Example 5, $L_p$ is obtained by setting $L_{pc} = 0$.

$$L_{\mathrm{p}} = L + 2L_{\mathrm{tb}} + 2L_{\mathrm{pc}} \quad \cdots\cdots (1)$$

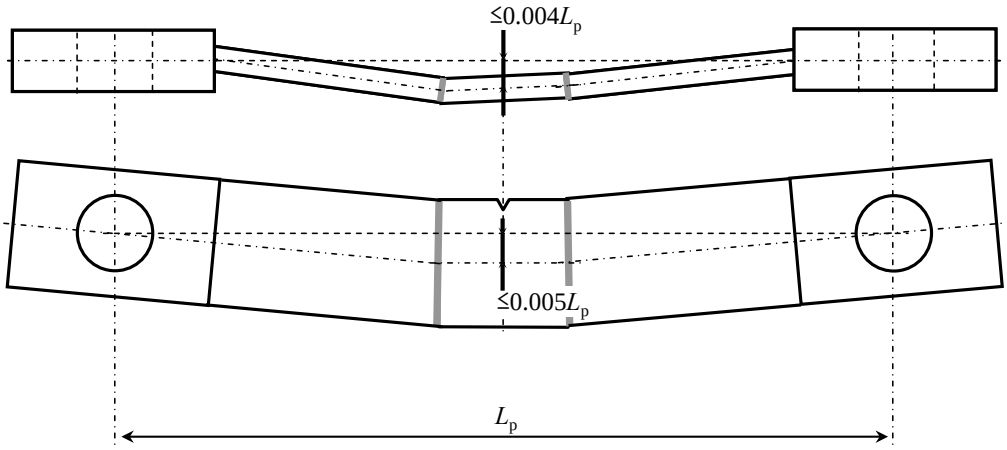
### 4.3 Welding of test specimen and tab plates

Test specimen, tab plates, and pin chucks shall be connected by welding. The welds shall have a sufficient force bearing strength.

As shown in Figure A3-4 (a), the flatness (angular distortion, linear misalignment) of the weld between a test specimen and a tab plate shall be 4 mm or less per 1 m. In the case of preloading, however, it is acceptable if the value after preloading satisfies this condition. As shown in Figure A3-4 (b), the accuracy of the in-plane loading axis shall be 0.5% or less of the distance between the pins, and the accuracy of the out-of-plane loading axis shall be 0.4% or less of the distance between the pins.




**(a) Flatness of weld between test specimen and tab plate**




**(b) Accuracy of in-plane and out-of-plane loading axes**

**Figure A3-4 Dimensional accuracy of weld between test specimen and tab plate**

**W31**
**(cont)**

## 5. Test methods

The following specifies methods for conducting the arrest toughness test.

### 5.1 Temperature control methods

A predetermined temperature gradient shall be established across a test specimen width by soldering at least nine thermocouples to the test specimen for temperature measurement and control.

Temperature gradient shall be established in accordance with the following conditions (1) through (3).

(1) A temperature gradient of 0.25 - 0.35°C/mm shall be established in a test specimen width range of 0.3*W* - 0.7*W*. When measuring the temperatures at the centre position of the test specimen thickness, it shall be kept within ±2°C for 10 minutes or more, whereas when measuring the temperatures on the front and back surface positions of the test specimen, it shall be kept within ±2°C for (10＋0.1*t* [mm]) minutes or more taking account of the time needed for soaking to the centre. If the temperature gradient at 0,3*W* - 0,7*W* is less than 0.25°C/mm, crack arrest may become difficult, and if the gradient is larger than 0.35°C/mm, the obtained arrest toughness may be too conservative.

(2) At the test specimen width centre position (i.e., 0.5*W*), and in the range of ±100 mm in the test specimen length direction, the deviation from the temperature at the centre position in the length direction shall be controlled within ±5°C. However, when temperature measurement is not performed at the centre position in the length direction, the average temperature at the closest position shall be used as the temperature at the centre position in the length direction.

(3) At the same position in the width direction, the deviation of the temperature on the front and back surfaces shall be controlled within ±5°C.

### 5.2 Crack initiation methods

Impact energy shall be applied to a test specimen to initiate a crack. However, if the energy is excessive, it may influence on the test results. In that case, the results shall be treated as invalid data in accordance with the judgment criteria specified in 7.2. It is desirable to use equation (2) and Figure A3-5 as guides for obtaining valid data.

$$\frac{E_{\mathrm{i}}}{t} \leq min\,(1.2\sigma - 40\,,\,200\,) \quad \cdots\cdots (2)$$

Where the variables have the following units: $E_i$ [J], $t$ [mm], and $\sigma$ [N/mm$^2$], and *min* means the minimum of the two values.

**W31**
**(cont)**

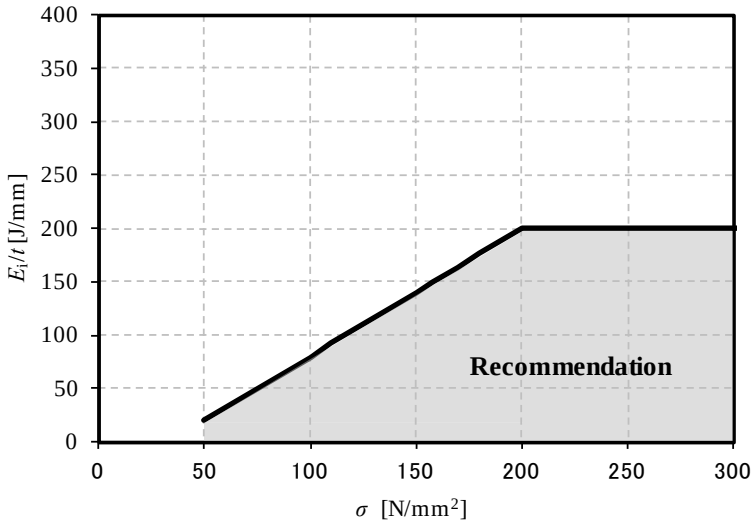



**Figure A3-5 Recommended range of impact energy**

## 6. Test procedures

The following specifies the procedures for testing brittle crack arrest toughness.

### 6.1 Pretest procedures

(1) Install an integrated specimen in the testing machine.

(2) Mount a cooling device on the test specimen. A heating device may also be mounted on the test specimen.

(3) Install an impact apparatus specified in 3.2, on the testing machine. Place an appropriate reaction force receiver as necessary.

Note: The above procedures (1) through (3) do not necessarily specify the order of implementation, and they may be completed, for example, on the day before the test.

(4) After checking that all measured values of the thermocouples indicate room temperature, start cooling. The temperature distribution and the holding time shall be as provided in the specifications in 5.1.

(5) Set an impact apparatus, as specified in 3.2 so that it can supply predetermined energy to the test specimen.

(6) Apply force to the test specimen until it reaches the predetermined value. This force is applied after temperature control to prevent autonomous crack initiation during force increase. Alternatively, temperature control may be implemented after loading. The loading rate and applied stress shall satisfy the conditions (a) and (b) described below, respectively.

(a) Loading rate
There is no specification of loading rate, but it shall be determined considering that an excessively slow loading rate may prolong the temperature control period, thereby allowing the temperature distribution to depart from the desired condition and an

**W31**
**(cont)**

excessively fast loading rate may cause over-shooting of the load.

(b) Applied stress/yield stress ratio
Applied stress shall be within the range shown by equation.

$$\sigma \leq \frac{2}{3}\sigma_{Y0} \quad \cdots\cdots (3)$$

As a guide, a value equal to 1/6 of $\sigma_{Y0}$ or more is desirable. If applied stress is larger than that specified by equation (3), the test may give a non-conservative result.

(7) To initiate a crack, the notch may be cooled further immediately before impact on the condition that the cooling does not disturb the temperature in the range of 0.3$W$ - 0.7$W$. The test temperature in this case shall be the measured temperature obtained from the temperature record immediately before the further notch cooling.

(8) Record the force value measured by a force recorder.

### 6.2 Loading procedures

(1) After holding a predetermined force for 30 seconds or more, apply an impact to the wedge using the impact apparatus. If a crack initiates autonomously and the exact force value at the time of the crack initiation cannot be obtained, the test is invalid.

(2) After the impact, record the force value measured by the force recorder.

(3) When the force after the impact is smaller than the test force, consider that crack initiation has occurred.

Note: An increase in the number of times of impact may cause a change in the shape of the notch of the test specimen. Since the number of impact has no effect on the value of brittle crack arrest toughness, no limit is specified for the number of impact. However, because the temperature gradient is often distorted by impact, the test shall be conducted again, beginning from temperature control when applying repeated impact to the wedge.

(4) When crack initiation, propagation, and arrest are observed, remove the force.

### 6.3 Procedures after testing

(1) Remove the impact apparatus.

(2) Remove the cooling device, thermocouples, and strain gauges.

(3) Return the temperature of the test specimen to room temperature. For that purpose, the test specimen may be heat-tinted using a gas burner or the like. If it is necessary to prevent heating of the fracture surface, this method shall be avoided.

(4) After gas-cutting an uncracked ligament, use the testing machine to cause ductile fracture, as necessary. Alternatively, it is also possible to gas-cut the uncracked ligament after using the testing machine to develop a ductile crack to a sufficient length.

**W31 (cont)**

### 6.4 Observation of fracture surfaces

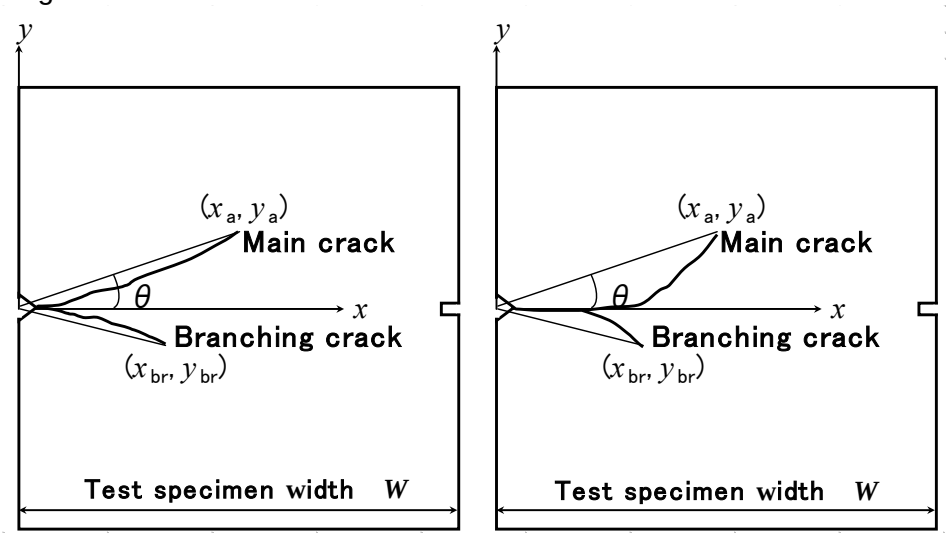
(1) Photograph the fracture surfaces and propagation path.

(2) Measure the longest length of the arrest crack tip in the plate thickness direction, and record the result as the arrest crack length. The arrest crack length shall include the notch length. In the case where a crack deviates from the direction vertical to the loading direction, the length projected to the plane vertical to the loading line is defined as the arrest crack length. In the following cases, however, judge the results according to the methods described for each case.

(a) Crack re-initiation
In the case where a brittle crack has re-initiated from an arrested crack, the original arrest position is defined as the arrest crack position. Here re-initiation is defined as the case where a crack and re-initiated cracks are completely separated by a stretched zone and brittle crack initiation from the stretched zone can be clearly observed. 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.

(b) Crack branching
In the case where a crack deviates from the direction vertical to the loading direction, the length projected to the plane vertical to the loading line is defined as the arrest crack length. Similarly, in the case of crack branching, the length of the longest branch crack projected to the plane vertical to the loading line is defined as the branch crack length. More specifically, from the coordinates ($x_a$, $y_a$) of the arrest crack tip position and the coordinates ($x_{br}$, $y_{br}$) of the branch crack tip position shown in Figure A3-6, obtain the angle $\theta$ from the $x$-axis and define $x_a$ as the arrest crack length, $a$. Here, $x$ is the coordinate in the test specimen width direction, and the side face of the impact side is set as $x = 0$; $y$ is the coordinate in the test specimen length direction, and the notch position is set as $y = 0$.

(3) Prepare a temperature distribution curve (line diagram showing the relation between the temperature and the distance from the test specimen top side) from the thermocouple measurement results, and obtain the arrest temperature $T$ corresponding to the arrest crack length.




**(a) Case of branching from notch brittle crack propagation** **(b) Case of branching during**

**Figure A3-6 Measurement methods of main crack and branch crack lengths**

**W31**
**(cont)**

## 7. Determination of arrest toughness

### 7.1 Judgment of arrested crack

When an arrested crack satisfies all of the conditions (a) through (d) below as shown in Figure A3-7, the length of the arrested crack determined by 6.4 is valid. If any of the conditions is not met, the arrest toughness calculated from 7.3 is invalid.

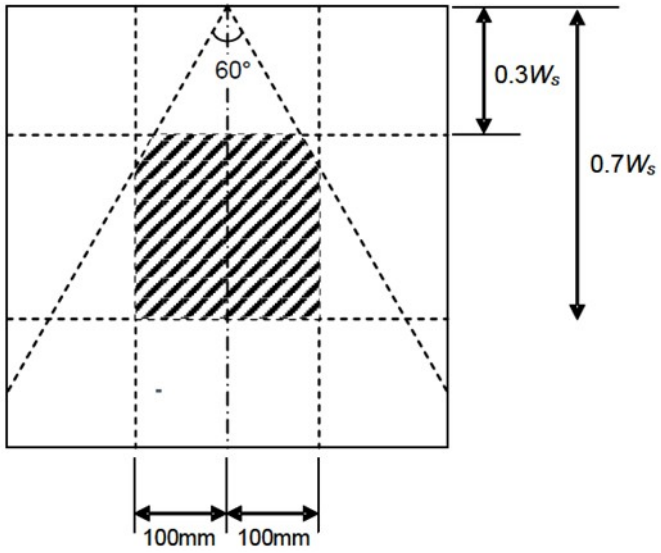



**Figure A3-7 Necessary conditions of arrest crack position**

(a) Conditions for crack propagation path:

All of the crack path from crack initiation to arrest shall be within the range shown in Figure A3-8. However, in the case where a main crack tip lies within this range but a part of the main crack passes outside the range, the arrest toughness may be 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 falls within ± 5% of $K$ for a straight crack of the same $a$. The calculation method of $K$s for the main crack and a straight crack is obtained from equation (4).

$$K = K_{\mathrm{I}} \cos^3\left(\frac{\phi}{2}\right) + 3K_{\mathrm{II}} \cos^2\left(\frac{\phi}{2}\right) \sin\left(\frac{\phi}{2}\right) \quad \cdots\cdots (4)$$

**W31**
**(cont)**

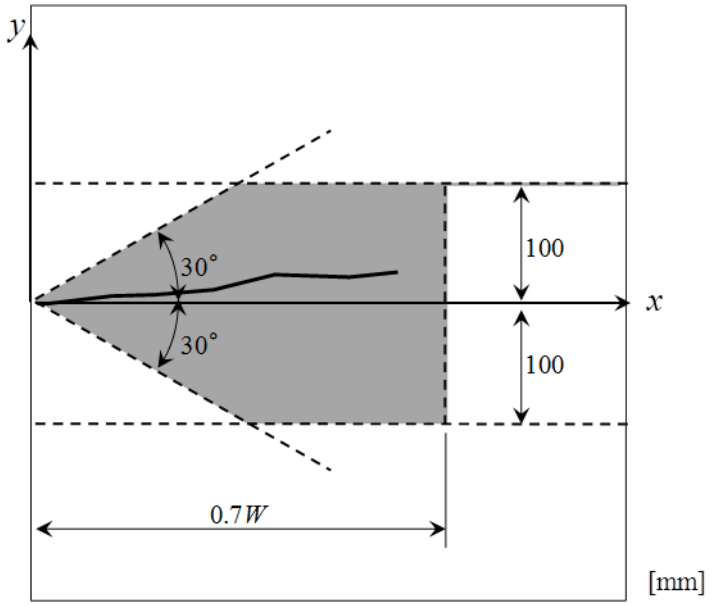



**Figure A3-8 Allowable range of main crack propagation path**

(b) Conditions for arrest crack length:

$$0.3 \le \left(\frac{a}{W}\right) \le 0.7 \quad \cdots\cdots (5)$$

$$\left(\frac{a}{t}\right) \ge 1.5 \quad \cdots\cdots (6)$$

$$\left(\frac{a}{L_p}\right) \le 0.15 \quad \cdots\cdots (7)$$

Note: Equation (7) ensures minimal influence of force drop at the centre of the specimen which might be caused by crack propagation and reflection of the stress wave at the two ends of the specimen. However, application of equation (7) is not necessarily required if the strain and the crack length have been dynamically measured and the value of the strain at the time of arrest is 90% or more of the static strain immediately before crack initiation.

(c) Conditions for crack straightness:

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

In the case where 50 mm $< |y_a| \le$ 100 mm and $|\theta| \le 30°$, the result is valid only when the temperature at $x = 0.5W$ and $y = \pm 100$ mm falls within ± 2.5°C of that at $x = 0.5W$ and $y = 0$.

(d) Conditions for crack branching:

$$\left(\frac{x_{br}}{x_a}\right) \le 0.6 \quad \cdots\cdots (9)$$

**W31 (cont)**

### 7.2 Assessment of impact energy

Impact energy shall satisfy equation (10). If it does not satisfy the equation, the value of arrest toughness calculated from the equations in 7.3 is invalid.

Conditions for impact energy:

$$\frac{E_i}{E_s + E_t} \le \frac{5a - 1050 + 1.4W}{0.7W - 150} \quad \text{where} \quad 0.3 \le \left(\frac{a}{W}\right) \le 0.7 \quad \cdots\cdots\cdots (10)$$

where the variables have the following units: $a$ [mm], and $W$ [mm]. $E_i$ is impact energy calculated from the equation (11). $E_s$ and $E_t$ are calculated from equations (12) and (13), respectively.

Note1: If equation (10) is not satisfied, the influence of impact energy on the stress intensity factor is too large to obtain an accurate arrest toughness.

Note2: In the case where the tab plates are multistage as shown in Figure A3-3 (b), calculate and total the strain energy of each tab plate using equation (12).

Note3: In the case where tab plate widths are tapered as shown in Figure A3-3 (d), calculate the strain energy based on elastostatics.

$$E_i = m\,g\,h \quad \cdots\cdots\cdots (11)$$

$$E_s = \frac{10^9 F^2}{2E}\frac{L}{W t} \quad \cdots\cdots\cdots (12)$$

$$E_t = \frac{10^9 F^2}{E}\left(\frac{L_{tb}}{W_{tb}\,t_{tb}} + \frac{L_{pc}}{W_{pc}\,t_{pc}}\right) \quad \cdots\cdots\cdots (13)$$

where the variables have the following units: $E_s$ [J], $E_t$ [J], $F$ [MN], $E$ [N/mm$^2$], $L$ [mm], $W$ [mm], and $t$ [mm].

### 7.3 Calculation of arrest toughness

The arrest toughness, $K_{ca}$, at the temperature, $T$, shall be calculated from equation (14) using the arrest crack length, $a$, and the applied stress, $\sigma$, judged by 7.1. Calculate $\sigma$ from equation (15).

$$K_{ca} = \sigma\sqrt{\pi a}\left[\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)\right]^{1/2} \quad \cdots\cdots\cdots (14)$$

$$\sigma = \frac{10^6 F}{W t} \quad \cdots\cdots\cdots (15)$$

where the variables have the following units: $F$ [MN], $W$ [mm], and $t$ [mm].

If the conditions specified in 7.1 and 7.2 are not satisfied, the $K_{ca}$ calculated from equation (14) is invalid.

**W31**
**(cont)**

## 8. Reporting

Using Table A3-4, the following items shall be reported:

(1) Test material: Steel type and yield stress at room temperature

(2) Testing machine: Capacity of the testing machine

(3) Test specimen dimensions: Thickness, width, length, angular distortion, and linear misalignment

(4) Integrated specimen dimensions: Tab plate thickness, tab plate width, integrated specimen length including the tab plates, and distance between the loading pins

(5) Test conditions: Applied force, applied stress, temperature gradient, impact energy, and the ratio of impact energy to the strain energy stored in the integrated specimen (sum of test specimen strain energy and tab plate strain energy)

(6) Test results

  (a) Judgment of arrest: Crack length, presence or absence of crack branching, main crack angle, presence or absence of crack re-initiation, and arrest temperature

  (b) Arrest toughness value

(7) Temperature distribution at moment of impact: Thermocouple position, temperature value, and temperature distribution

(8) Test specimen photographs: Crack propagation path (one side), and brittle crack fracture surface (both sides)

(9) Dynamic measurement results: History of crack propagation velocity, and strain change at pin chucks

Note: Item (9) shall be reported as necessary.

**W31**
**(cont)**

**Table A3-4 Report sheet for brittle crack arrest test results**

| Item | Details | | Symbol | Conditions/ Results | Unit | Valid/ Invalid |
|---|---|---|---|---|---|---|
| (1) Test material | Steel type | | — | | — | — |
| | Yield stress at room temperature | | $\sigma_{Y0}$ | | N/mm$^2$ | — |
| (2) Test equipment | Testing machine capacity | | — | | MN | — |
| (3) Test specimen dimensions | Thickness | | $t$ | | mm | |
| | Width | | $W$ | | mm | |
| | Length | | $L$ | | mm | |
| | Angular distortion + linear misalignment | | — | | mm/m | |
| (4) Integrated specimen dimensions | Tab plate thickness | | $t_{tb}$ | | mm | |
| | Tab plate width | | $W_{tb}$ | | mm | |
| | Test specimen length including a tab plate | | $L + L_{tb}$ | | mm | |
| | Distance between loading pins | | $L_p$ | | mm | |
| (5) Test conditions | Applied force | | $F$ | | MN | |
| | Applied stress | | $\sigma$ | | N/mm$^2$ | |
| | Temperature gradient | | — | | °C /mm | |
| | Impact energy | | $E_i$ | | J | |
| | Ratio of impact energy to strain energy stored in integrated specimen | | $E_i/(E_s+E_t)$ | | — | |
| (6) Test results | Judgment of crack propagation/arrest | Crack length | $a$ | | mm | |
| | | Presence/absence of crack branching | — | | — | — |
| | | Ratio of branch crack length to main crack | $x_{br}/x_a$ | | — | |
| | | Main crack angle | $\theta$ | | degree (°) | |
| | | Presence/absence of crack re-initiation | — | | — | |
| | | Temperature at crack arrest position | $T$ | | °C | |
| | Arrest toughness value | | $K_{ca}$ | | N/mm$^{3/2}$ | |
| (7) Temperature distribution at moment of impact | Temperature measurement position | | — | Attached | — | — |
| | Temperature at each temperature measurement position | | — | Attached | °C | — |
| | Temperature distribution curve | | — | Attached | — | |
| (8) Test specimen photographs | Crack propagation path | | — | Attached | — | |
| | Brittle crack fracture surface (both sides) | | — | Attached | — | |
| (9) Dynamic measurement results | History of crack propagation velocity | | — | Attached | — | |
| | Strain change at pin chucks | | — | Attached | — | |

**W31**
**(cont)**

## Annex 3 - Appendix A

## Method for obtaining $K_{ca}$ at a specific temperature and the evaluation

### A.1 General

This Appendix specifies the method for conducting multiple tests specified in Annex 3 of this UR to obtain $K_{ca}$ value at a specific temperature $T_D$.

### A.2 Method

A number of experimental data show dependency of $K_{ca}$ on arrest temperature, as expressed by equation (A.1), where $T_K$ [K] (= T [°C]＋273), $c$ and $K_0$ are constants.

$$K_{\mathrm{ca}} = K_0 \exp\left(\frac{c}{T_{\mathrm{K}}}\right) \quad \text{..... (A.1)}$$

The arrest toughness at a required temperature $T_D$ [K] can be obtained by following the procedures below.

(1) Obtain at least four valid $K_{ca}$ data.

(2) Approximating log $K_{ca}$ by a linear expression of $1/T_K$, determine the coefficients log $K_0$ and $c$ for the data described in paragraph (1) by using the least square method.

$$\log K_{\mathrm{ca}} = \log K_0 + c\frac{1}{T_{\mathrm{K}}} \quad \text{..... (A.2)}$$

(3) Obtain the value of $(K_{ca}/K_0)\exp(c/T_K)$ for each data item. When the number of data outside the range of 0.85 through 1.15 does not exceed, the least square method used in paragraph (2) is considered valid. Here is an integer obtained by rounding down the value of (number of all data divided by 6). If this condition is not met, conduct additional tests to add at least two data and apply the procedure in paragraph (2) to the data.

(4) 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 $T_K = c/\log(K_{ca}/K_0)$. If the condition specified in paragraph (3) is not met, these estimated values are treated as reference values.

### A.3 Evaluation

The straight-line approximation of arrhenius plot for valid $K_{ca}$ data by interpolation method are to comply with either the following (1) or (2):

(1) The evaluation temperature of $K_{ca}$ (i.e. - 10 degree C) is located between the upper and lower limits of the arrest temperature, with the $K_{ca}$ corresponding to the evaluation temperature not lower than the required $K_{ca}$ (e.g. 6,000 N/mm$^{3/2}$ or 8,000 N/mm$^{3/2}$), as shown in Fig. A3-A.1.

**W31**
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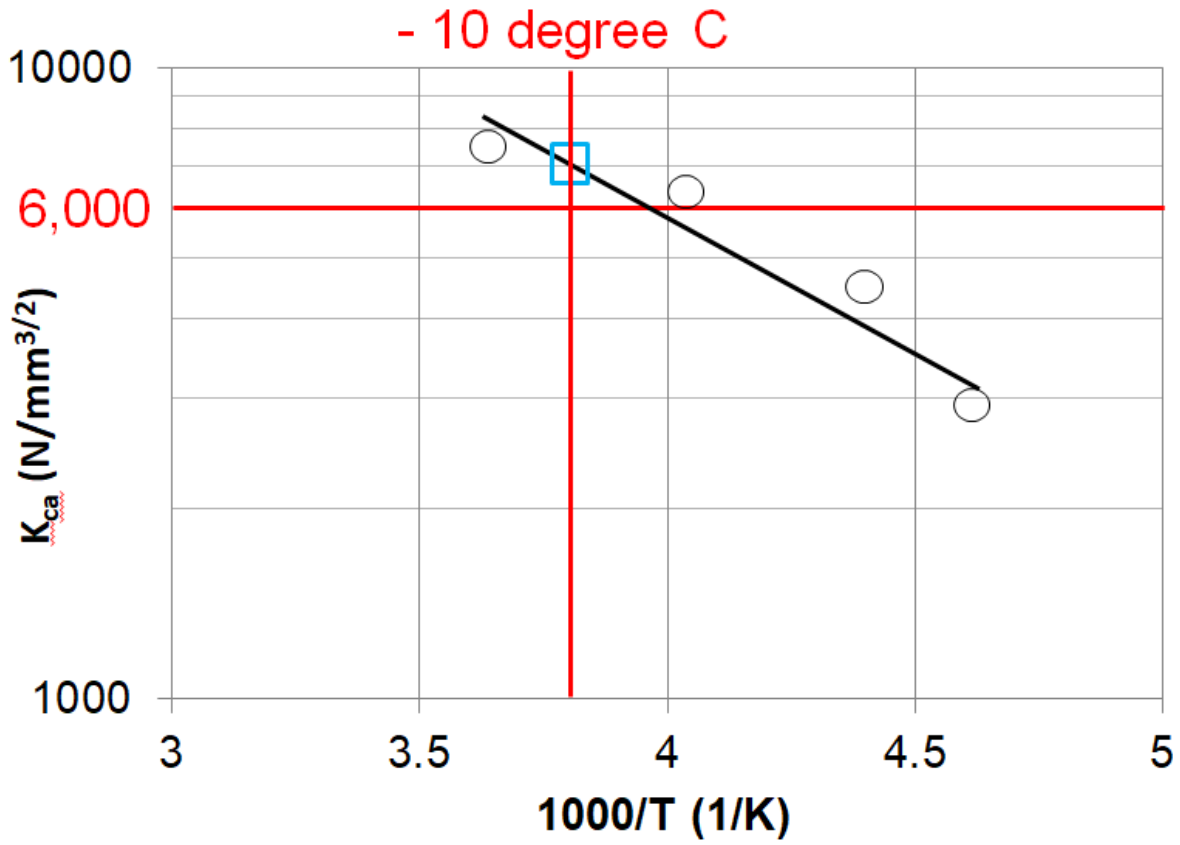


**Fig. A3-A.1 Example for evaluation of $K_{ca}$ at - 10 degree C**

(2) The temperature corresponding to the required $K_{ca}$ (e.g. 6,000 N/mm$^{3/2}$ or 8,000 N/mm$^{3/2)}$ is located between the upper and lower limits of the arrest temperature, with the temperature corresponding to the required $K_{ca}$ not higher than the evaluation temperature (i.e. -10 degree C), as shown in Fig. A3-A.2.

**W31**
**(cont)**

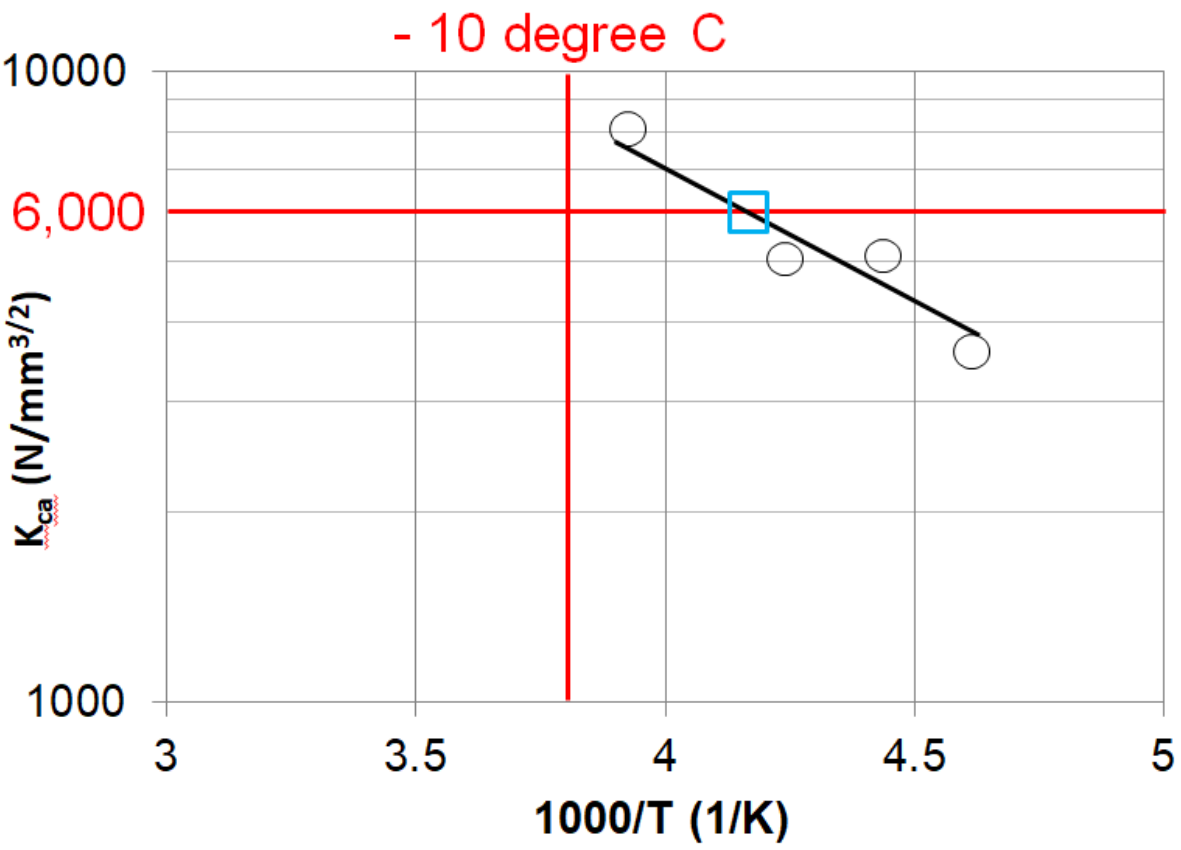


**Fig. A3-A.2 Example for evaluation of temperature corresponding to the required $K_{ca}$**

If both of (1) and (2) above are not satisfied, conduct additional tests to satisfy this condition.

**W31**
**(cont)**

## Annex 3 - Appendix B

## Double tension type arrest test

### B.1 Features of this test method

A double tension type arrest test specimen consists of a main plate and a secondary loading tab. The main plate is a test plate for evaluating brittle 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 tension 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.

The narrow connection part of the main plate and the secondary loading tab in this test suppress the flow of the tension stresses of the secondary loading tab into the main plate. The values of arrest toughness obtained by this method can be considered the same as the results obtained by the brittle crack arrest toughness test specified in Annex 3 of this UR.

The specifications described in Annex 3 of this UR shall be applied to conditions not mentioned in this Appendix B.

### B.2 Test specimen shapes

The recommended shapes of the entire double tension type arrest test specimen and the secondary loading tab are shown in Figures A3-B.1 and A3-B.2, respectively. Clause 4.2 of Annex 3 of this UR is applied to the shapes of the tab plates and pin chucks.

Note: Because of the narrowness of the connection part, slight crack deviation may lead to failure of the crack to enter the main plate. The optimum shape design of the secondary loading tab depends on the type of steel and testing conditions.

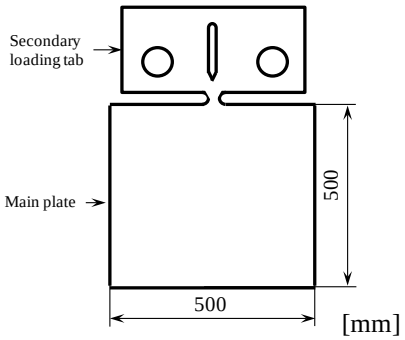


**Figure A3-B.1 Example of shape of entire test specimen**

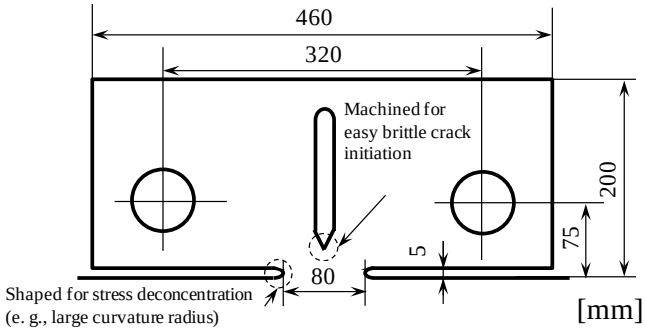


**Figure A3-B.2 Example of shape of secondary loading tab**

**W31**
**(cont)**

### B.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 5**,** Annex 3 of this UR. In addition, in the double tension type arrest test, the secondary loading tab must be cooled. The secondary loading tab is cooled without affecting the temperature gradient of the main plate. As in the cooling method for test specimens described in Annex 3 of this UR, cooling may be applied using a cooling box and a coolant. The temperature of the secondary loading tab can be measured using thermocouples as described in Annex 3 of this UR.

### B.4 Secondary loading method

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

#### B.4.1 Holding methods of secondary loading device

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

#### B.4.2 Loading system

A hydraulic type loading system is most suitable for applying a force to the secondary loading tab. However, other methods may be used. Clause 4.2 of Annex 3 of this UR is applied to the shapes of the tab plates and pin chucks.

#### B.4.3 Loading method

The method of loading the secondary loading tab shall be a pin type loading method. A loading method other than a pin type may be used by agreement among the parties concerned. The loading rate is not specifically specified because it does not have a direct influence on the crack arrest behavior of the main plate.

**W31**
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## Annex 4 Outline of requirements for undertaking isothermal Crack Arrest Temperature (CAT) test

### 1. Scope of application

1.1 Annex 4 is to be applied according to the scope defined in UR W31.

1.2 Annex 4 specifies the requirements for test procedures and test conditions when using the isothermal crack arrest test to determine a valid test result under isothermal conditions and in order to establish the crack arrest temperature (CAT). Annex 4 is applicable to steels with thickness over 50mm and not greater than 100mm.

1.3 This method uses an isothermal temperature in the test specimen being evaluated. Unless otherwise specified in this Annex 4, the other test parameters are to be in accordance with Annex 3.

1.4 Table 3 of UR W31 gives the relevant requirements for the brittle crack arrest property described by the crack arrest temperature (CAT).

1.5 The manufacturer is to submit the test procedure to the Classification Society for review prior to testing.

### 2 Symbols and their significance

2.1 Table A4-1 supplements Table A3-1 in Annex 3 with specific symbols for the isothermal test.

**W31**
**(cont)**

**Table A4-1 Nomenclature supplementary to Table A3-1**

| Symbol | Unit | Significance |
|---|---|---|
| $t$ | mm | Test specimen thickness |
| $L$ | mm | Test specimen length |
| $W$ | mm | Test specimen width |
| $a_{MN}$ | mm | Machined notch length on specimen edge |
| $L_{SG}$ | mm | Side groove length on side surface from the specimen edge. $L_{SG}$ is defined as a groove length with constant depth except a curved section in depth at side groove end. |
| $d_{SG}$ | mm | Side groove depth in section with constant depth |
| $L_{EB\ -\ min}$ | mm | Minimum length between specimen edge and electron beam re-melting zone front |
| $L_{EB-s1,\ -s2}$ | mm | Length between specimen edge and electron beam re-melting zone front appeared on both specimen side surfaces |
| $L_{LTG}$ | mm | Local temperature gradient zone length for brittle crack runway |
| $a_{arrest}$ | mm | Arrested crack length |
| $T_{target}$ | °C | Target test temperature |
| $T_{test}$ | °C | Defined test temperature |
| $T_{arrest}$ | °C | Target test temperature at which valid brittle crack arrest behaviour is observed |
| $\sigma$ | N/mm$^2$ | Applied test stress at cross section of $W$ x $t$ |
| SMYS | N/mm$^2$ | Specified minimum yield strength of the tested steel grade to be approved |
| CAT | °C | Crack arrest temperature, the lowest temperature, $T_{arrest}$, at which running brittle crack is arrested |

## 3 Testing equipment

3.1 The test equipment to be used is to be of the hydraulic type of sufficient capacity to provide a tensile load equivalent to ⅔ of SMYS of the steel grade to be approved.

3.2 The temperature control system is to be equipped to maintain the temperature in the specified region of the specimen within ±2°C from $T_{target}$.

3.3 Methods for initiating the brittle crack may be of drop weight type, air gun type or double tension tab plate type.

3.4 The detailed requirements for testing equipment are specified in 3 of Annex 3.

## 4 Test specimens

### 4.1 Impact type crack initiation

4.1.1 Test specimens are to be in accordance with 4 of Annex 3, unless otherwise specified in this Annex.

4.1.2 Specimen dimensions are shown in Figure A4-1. The test specimen width, $W$ shall be

**W31**
**(cont)**

500mm. The test specimen length, *L* shall be equal to or greater than 500mm.

4.1.3 V-shape notch for brittle crack initiation is machined on the specimen edge of the impact side. The whole machined notch length shall be equal to 29mm with a tolerance range of ±1mm.

4.1.4 Requirements for side grooves are described in 4.4.

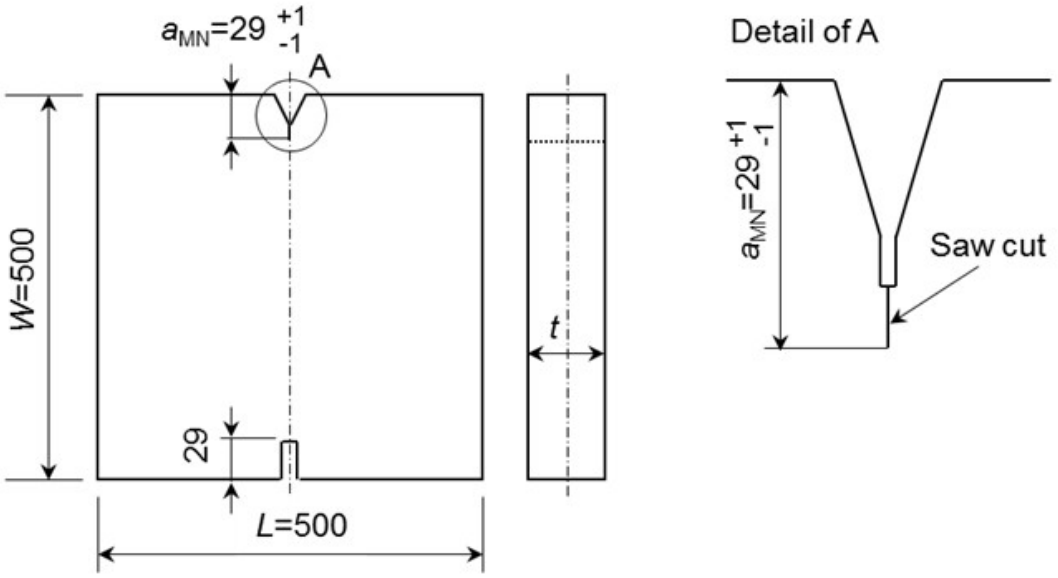


**Figure A4-1 Test specimen dimensions for an impact type specimen**

NOTE: Saw cut notch radius may be machined in the range 0.1mmR and 1mmR in order to control a brittle crack initiation at test.

**4.2 Double tension type crack initiation**

4.2.1 Reference shall be made to Appendix B in Annex 3 for the shape and sizes in secondary loading tab and secondary loading method for brittle crack initiation.

4.2.2 In a double tension type test, the secondary loading tab plate may be subject to further cooling to enhance an easy brittle crack initiation.

**4.3 Embrittled zone setting**

4.3.1 An embrittled zone shall be applied to ensure the initiation of a running brittle crack. Either Electron Beam Welding (EBW) or Local Temperature Gradient (LTG) may be adopted to facilitate the embrittled zone.

4.3.2 In EBW embrittlement, electron beam welding is applied along the expected initial crack propagation path, which is the centre line of the specimen in front of the machined V- notch.

4.3.3 The complete penetration through the specimen thickness is required along the embrittled zone. One side EBW penetration is preferable, but dual sides EB penetration may be also adopted when the EBW power is not enough to achieve the

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**(cont)**

complete penetration by one side EBW.

4.3.4 The EBW embrittlement is recommended to be prepared before specimen contour machining.

4.3.5 In EBW embrittlement, zone shall be of an appropriate quality.

Note: EBW occasionally behaves in an un-stable manner at start and end points. EBW line is recommended to start from the embrittled zone tip side to the specimen edge with an increasing power control or go/return manner at start point to keep the stable EBW.

4.3.6 In LTG system, the specified local temperature gradient between machined notch tip and isothermal test region is regulated after isothermal temperature control. LTG temperature control is to be achieved just before brittle crack initiation, nevertheless the steady temperature gradient through the thickness shall be ensured.

**4.4 Side grooves**

4.4.1 Side grooves on side surface can be machined along the embrittled zone to keep brittle crack propagation straight. Side grooves shall be machined in the specified cases as specified in this section.

4.4.2 In EBW embrittlement, side grooves are not necessarily mandatory. Use of EBW avoids the shear lips. However, when shear lips are evident on the fractured specimen, e.g. shear lips over 1mm in thickness in either side then side grooves should be machined to suppress the shear lips.

4.4.3 In LTG embrittlement, side grooves are mandatory. Side grooves with the same shape and size shall be machined on both side surfaces.

4.4.4 The length of side groove, $L_{SG}$ shall be no shorter than the sum of the required embrittled zone length of 150mm.

4.4.5 When side grooves would be introduced, the side groove depth, the tip radius and the open angle are not regulated, but are adequately selected in order to avoid any shear lips over 1mm thickness in either side. An example of side groove dimensions are shown in Figure A4-2.

4.4.6 Side groove end shall be machined to make a groove depth gradually shallow with a curvature larger than or equal to groove depth, $d_{SG}$. Side groove length, $L_{SG}$ is defined as a groove length with constant depth except a curved section in depth at side groove end.

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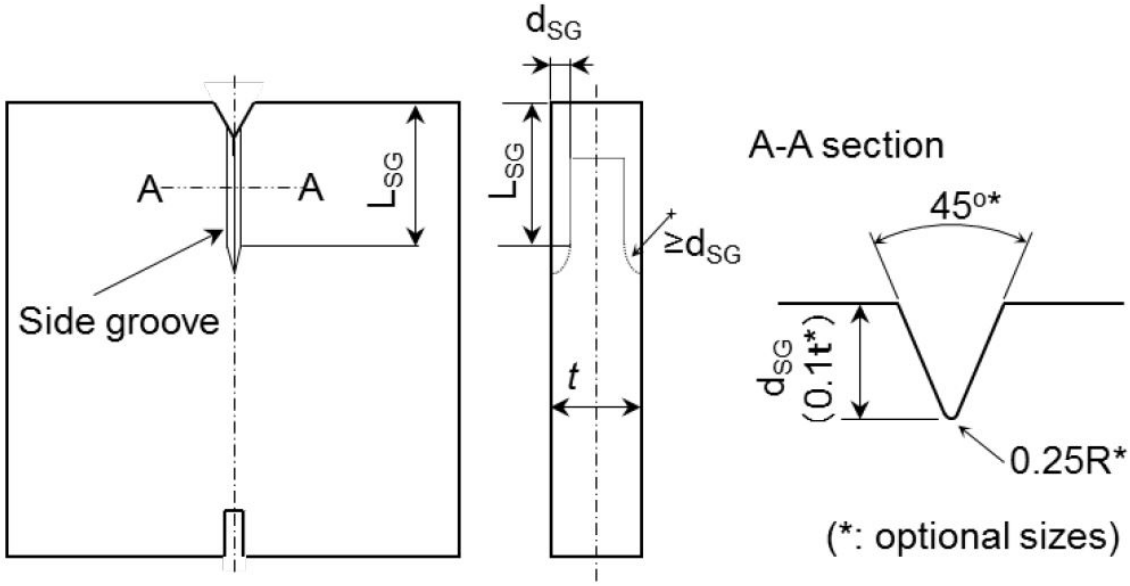


**Figure A4-2 Side groove configuration and dimensions**

**4.5 Nominal length of embrittled zone**

4.5.1 The length of embrittled zone shall be nominally equal to 150mm in both systems of EBW and LTG.

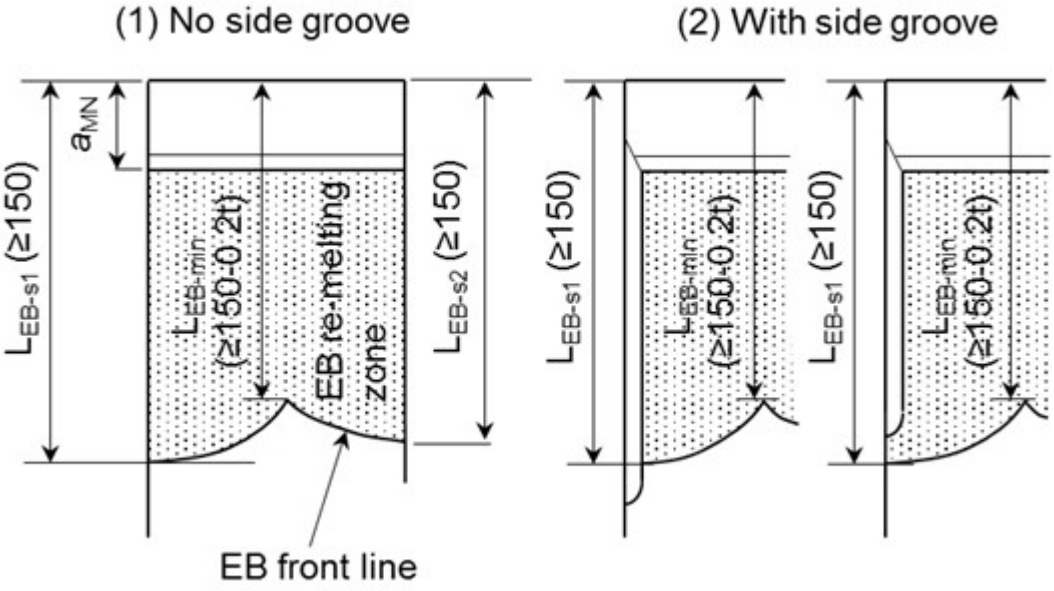


**Figure A4-3 Definition of EBW length**

4.5.2 EBW zone length is regulated by three measurements on the fracture surface after test as shown in Figure A4-3, $L_{EB-min}$ between specimen edge and EBW front line, and $L_{EB-s1}$ and $L_{EB-s2}$.

**W31 (cont)**

4.5.3 The minimum length between specimen edge and EBW front line, $L_{EB\text{-}min}$ should be no smaller than 150mm. However, it can be acceptable even if $L_{EB\text{-}min}$ is no smaller than 150mm-0.2$t$, where $t$ is specimen thickness. When $L_{EB\text{-}min}$ is smaller than 150mm, a temperature safety margin shall be considered into $T_{test}$ (See 8.1.2).

4.5.4 Another two are the lengths between specimen edge and EBW front appeared on both side surfaces, as denoted with $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$. Both of $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$ shall be no smaller than 150mm.

4.5.5 In LTG system, $L_{LTG}$ is set as 150mm.

### 4.6 Tab plate / pin chuck details and welding of test specimen to tab plates

4.6.1 The configuration and size of tab plates and pin chucks shall be referred to 4.2 of Annex 3. The welding distortion in the integrated specimen, which is welded with specimen, tab plates and pin chucks, shall be also within the requirement in 4.3 of Annex 3.

## 5 Test method

### 5.1 Preloading

5.1.1 Preloading at room temperature can be applied to avoid unexpected brittle crack initiation at test. The applied load value shall be no greater than the test stress. Preloading can be applied at higher temperature than ambient temperature when brittle crack initiation is expected at preloading process. However, the specimen shall not be subjected to temperature higher than 100°C.

### 5.2 Temperature measurement and control

5.2.1 Temperature control plan showing the number and position of thermocouples is to be in accordance with this section.

5.2.2 Thermocouples are to be attached to both sides of the test specimen at a maximum interval of 50mm in the whole width and in the longitudinal direction at the test specimen centre position (0.5 $W$) within the range of ±100mm from the centreline in the longitudinal direction, refer to Figure A4-4.

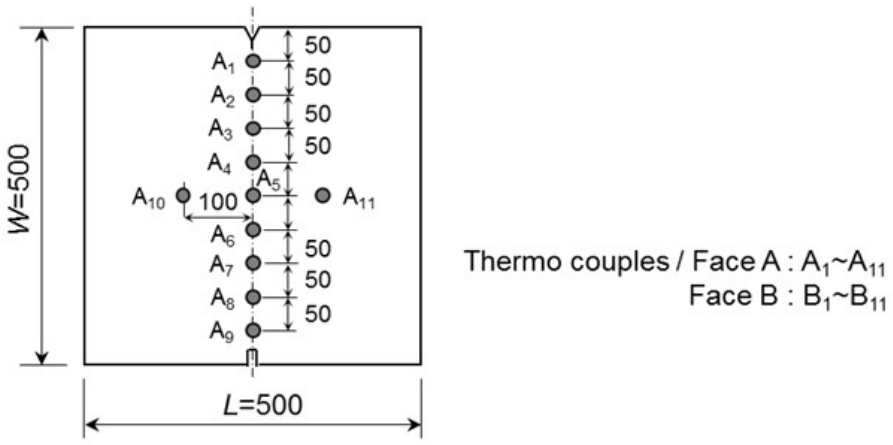


**Figure A4-4 Locations of temperature measurement**

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**(cont)**

5.2.3 For EBW embrittlement

5.2.3.1 The temperatures of the thermocouples across the range of 0.3*W*~0.7*W* in both width and longitudinal directions are to be controlled within ± 2°C of the target test temperature, $T_{target}$.

5.2.3.2 When all measured temperatures across the range of 0.3*W*~0.7*W* have reached $T_{target}$, steady temperature control shall be kept at least for 10 + 0.1 x *t* [mm] minutes to ensure a uniform temperature distribution into mid-thickness prior to applying test load.

5.2.3.3 The machined notch tip can be locally cooled to easily initiate brittle crack. Nevertheless, the local cooling shall not disturb the steady temperature control across the range of 0.3*W*~0.7*W*.

5.2.4 For LTG embrittlement:

5.2.4.1 In LTG system, in addition to the temperature measurements shown in Figure A4-4, the additional temperature measurement at the machine notch tip, $A_0$ and $B_0$ is required. Thermocouples positions within LTG zone are shown in Figure A4-5.

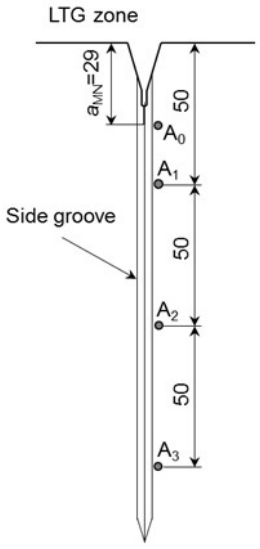


**Figure A4-5 Detail of LTG zone and additional thermocouple $A_0$**

5.2.4.2 The temperatures of the thermocouples across the range of 0.3*W*~0.7*W* in both width and longitudinal directions are to be controlled within ± 2°C of the target test temperature, $T_{target}$. However, the temperature measurement at 0.3*W* (location of $A_3$ and $B_3$) shall be in accordance with 5.2.4.6 below.

5.2.4.3 Once the all measured temperatures across the range of 0.3*W*~0.7*W* have reached $T_{target}$, steady temperature control shall be kept at least for 10 + 0.1 x *t* [mm] minutes to ensure a uniform temperature distribution into mid-thickness, then the test load is applied.

5.2.4.4 LTG is controlled by local cooling around the machined notch tip. LTG profile shall be recorded by the temperature measurements from $A_0$ to $A_3$ shown in Figure A4-6.

**W31 (cont)**

5.2.4.5 LTG zone is established by temperature gradients in three zones, Zone I, Zone II and Zone III. The acceptable range for each temperature gradient is listed Table A4-2.

5.2.4.6 Two temperature measurements at $A_2$, $B_2$ and $A_3$, $B_3$ shall be satisfied the following requirements:

$T$ at $A_3$, $T$ at $B_3 < T_{target} - 2^oC$

$T$ at $A_2 < T$ at $A_3 - 5^oC$

$T$ at $B_2 < T$ at $B_3 - 5^oC$

5.2.4.7 No requirements for $T$ at $A_0$ and $T$ at $A_1$ temperatures when $T$ at $A_3$ and $T$ at $A_2$ satisfy the requirements above. Face B is the same.

5.2.4.8 The temperatures from $A_0$, $B_0$ to $A_3$, $B_3$ should be decided at test planning stage refer to Table A4-2 which gives the recommended temperature gradients in three zones, Zone I, Zone II and Zone III in LTG zone.

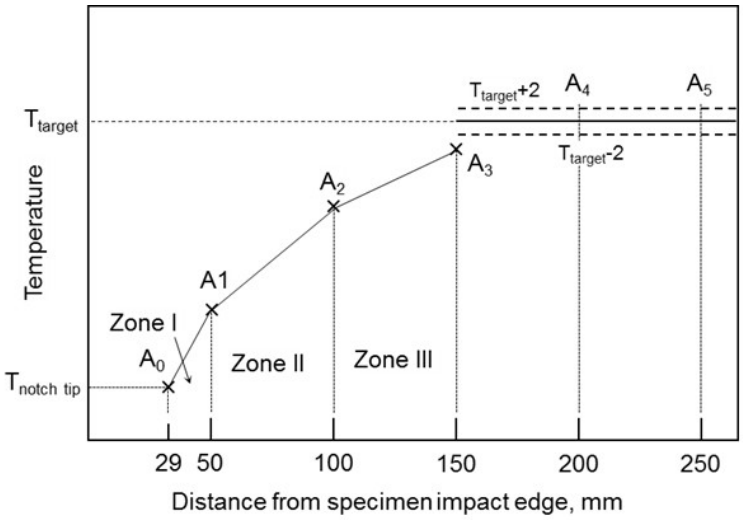


**Figure A4-6 Schematic temperature gradient profile in LTG zone**

**Table A4-2 Acceptable LTG range**

| Zone | Location from edge | Acceptable range of temperature gradient |
|---|---|---|
| Zone I | 29mm – 50mm | 2.00 ˚C/mm – 2.30 ˚C/mm |
| Zone II | 50mm – 100mm | 0.25 ˚C/mm – 0.60 ˚C/mm |
| Zone III[1)] | 100mm – 150mm | 0.10 ˚C/mm – 0.20 ˚C/mm |

Note 1: The Zone III arrangement is mandatory

5.2.4.9 The temperature profile in LTG zone mentioned above shall be ensured after holding time at least for 10 + 0.1 x $t$ [mm] minutes to ensure a uniform temperature distribution into mid-thickness before brittle crack initiation.

5.2.4.10 The acceptance of LTG in the test shall be decided from Table A4-2 based on the measured temperatures from $A_0$ to $A_3$.

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5.2.5 For double tension type crack initiation specimen:

5.2.5.1 Temperature control and holding time at steady state shall be the same as the case of EBW embrittlement specified in 5.2.3 or the case of LTG embrittlement specified in Section 5.2.4.

**5.3 Loading and brittle crack initiation**

5.3.1 Prior to testing, a target test temperature ($T_{target}$) shall be selected.

5.3.2 Test procedures are to be in accordance with 6 of Annex 3 except that the applied stress is to be ⅔ of SMYS of the steel grade tested.

5.3.3 The test load shall be held at the test target load or higher for a minimum of 30 seconds prior to crack initiation.

5.3.4 Brittle crack can be initiated by impact or secondary tab plate tension after all of the temperature measurements and the applied force are recorded.

**6. Measurements after test and test validation judgement**

**6.1 Brittle crack initiation and validation**

6.1.1 If brittle crack spontaneously initiates before the test force is achieved or the specified hold time at the test force is not achieved, the test shall be invalid.

6.1.2 If brittle crack spontaneously initiates without impact or secondary tab tension but after the specified time at the test force is achieved, the test is considered as a valid initiation. The following validation judgments of crack path and fracture appearance shall be examined.

**6.2 Crack path examination and validation**

6.2.1 When brittle crack path in embrittled zone deviates from EBW line or side groove in LTG system due to crack deflection and/or crack branching, the test shall be considered as invalid.

6.2.2 All of the crack path from embrittled zone end shall be within the range shown in Figure A4-7. If not, the test shall be considered as invalid.

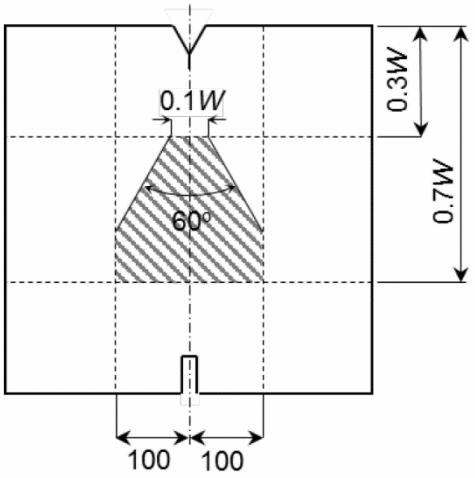


**Figure A4-7 Allowable range of main crack propagation path**

**W31 (cont)**

### 6.3 Fracture surface examination, crack length measurement and their validation

6.3.1 Fracture surface shall be observed and examined. The crack “initiation” and “propagation” are to be checked for validity and judgements recorded. The crack “arrest” positions are to be measured and recorded.

6.3.2 When crack initiation trigger point is clearly detected at side groove root, other than the V-notch tip, the test shall be invalid.

6.3.3 In EBW embrittlement setting, EBW zone length is quantified by three measurements of $L_{EB\text{-}s1}$, $L_{EB\text{-}s2}$ and $L_{EB\text{-}min}$, which are defined in 4.5. When either or both of $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$ are smaller than 150mm, the test shall be invalid. When $L_{EB\text{-}min}$ is smaller than 150mm-0.2$t$, the test shall be invalid.

6.3.4 When the shear lip with thickness over 1mm in either side near side surfaces of embrittled zone are visibly observed independent of the specimens with or without side grooves, the test shall be invalid.

6.3.5 In EBW embrittlement setting, the penetration of brittle crack beyond the EBW front line shall be visually examined. When any brittle fracture appearance area continued from the EB front line is not detected, the test shall be invalid.

6.3.6 The weld defects in EBW embrittled zone shall be visually examined. If detected, it shall be quantified. A projecting length of defect on the thickness line through EB weld region along brittle crack path shall be measured, and the total occupation ratio of the projected defect part to the total thickness is defined as defect line fraction (See Figure A4-8). When the defects line fraction is larger than 10 %, the test shall be invalid.

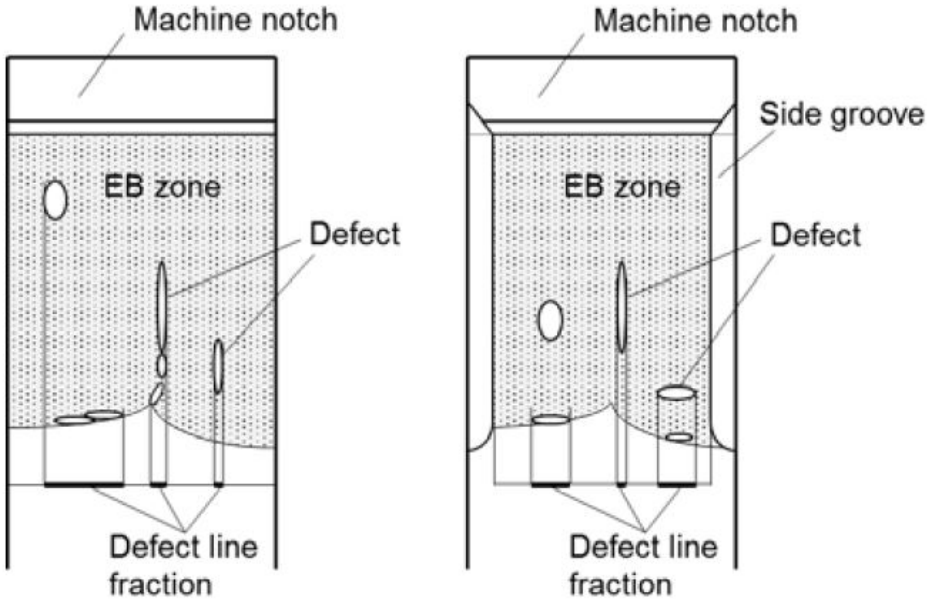


**Fig. A4-8 Counting procedure of defect line fraction**

6.3.7 In EBW embrittlement by dual sides’ penetration, a gap on embrittled zone fracture surface which is induced by miss meeting of dual fusion lines is visibly detected at an overlapped line of dual side penetration, the test shall be invalid.

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## 7 Judgement of "arrest" or "propagate"

7.1 The final test judgment of "arrest", "propagate" or "invalid" is decided by the following requirements of 7.2 through 7.6.

7.2 If initiated brittle crack is arrested and the tested specimen is not broken into two pieces, the fracture surfaces should be exposed with the procedures specified in 6.3 and 6.4 of Annex 3.

7.3 When the specimen was not broken into two pieces during testing, the arrested crack length, $a_{arrest}$ shall be measured on the fractured surfaces. The length from the specimen edge of impact side to the arrested crack tip (the longest position) is defined as $a_{arrest}$.

7.4 For LTG and EBW, $a_{arrest}$ shall be greater than $L_{LTG}$ and $L_{EB\text{-}s1}$, $L_{EB\text{-}s2}$ or $L_{EB\text{-}min}$. If not, the test shall be considered as invalid.

7.5 Even when the specimen was broken into two pieces during testing, it can be considered as "arrest" when brittle crack re-initiation is clearly evident. Even in the fracture surface all occupied by brittle fracture, when a part of brittle crack surface from embrittled zone is continuously surrounded by thin ductile tear line, the test can be judged as re-initiation behaviour. If so, the maximum crack length of the part surrounded tear line can be measured as $a_{arrest}$. If re-initiation is not visibly evident, the test is judged as "propagate".

7.6 The test is judged as "arrest" when the value of $a_{arrest}$ is no greater than $0.7W$. If not, the test is judged as "propagate".

## 8 $T_{test}$, $T_{arrest}$ and CAT determination

### 8.1 $T_{test}$ determination

8.1.1 It shall be ensured on the thermocouple measured record that all temperature measurements across the range of $0.3W$ ~ $0.7W$ in both width and longitudinal direction are in the range of $T_{target}$ ±2°C at brittle crack initiation. If not, the test shall be invalid. However, the temperature measurement at $0.3W$ (location of $A_3$ and $B_3$) in LTG system shall be exempted from this requirement.

8.1.2 If $L_{EB\text{-}min}$ in EBW embrittlement is no smaller than 150mm, $T_{test}$ can be defined to equal with $T_{target}$. If not, $T_{test}$ shall be equaled with $T_{target}$ + 5˚C.

8.1.3 In LTG embrittlement, $T_{test}$ can be equaled with $T_{target}$.

8.1.4 The final arrest judgment at $T_{test}$ is concluded by at least two tests at the same test condition which are judged as "arrest".

### 8.2 $T_{arrest}$ determination

8.2.1 When at least repeated two "arrest" tests appear at the same $T_{target}$, brittle crack arrest behaviour at $T_{target}$ will be decided ($T_{arrest}$ = $T_{target}$).When a "propagate" test result is included in the multiple test results at the same $T_{target}$, the $T_{target}$ cannot to be decided as $T_{arrest}$.

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### 8.3 CAT determination

8.3.1 When CAT is determined, one “propagate” test is needed in addition to two “arrest” tests. The target test temperature, $T_{target}$ for “propagate” test is recommended to select 5°C lower than $T_{arrest}$. The minimum temperature of $T_{arrest}$ is determined as CAT.

8.3.2 With only the “arrest” tests, without “propagation” test, it is decided only that CAT is lower than $T_{test}$ in the two “arrest” tests, i.e. not deterministic CAT.

## 9 Reporting

The following items are to be reported:

(i) Test material: grade and thickness

(ii) Test machine capacity

(iii) Test specimen dimensions: thickness $t$; width $W$ and length $L$; notch details and length $a_{MN}$, side groove details if machined;

(iv) Embrittled zone type: EBW or LTG embrittlement

(v) Integrated specimen dimensions: Tab plate thickness, tab plate width, integrated specimen unit length including the tab plates, and distance between the loading pins, angular distortion and linear misalignment

(vi) Brittle crack trigger information: impact type or double tension. If impact type, drop weight type or air gun type, and applied impact energy.

(vii) Test conditions; Applied load; preload stress, test stress
- Judgements for preload stress limit, hold time requirement under steady test stress.

(viii) Test temperature: complete temperature records with thermocouple positions for measured temperatures (figure and/or table) and target test temperature.

- Judgements for temperature scatter limit in isothermal region.

- Judgement for local temperature gradient requirements and holding time requirement after steady local temperature gradient before brittle crack trigger, if LTG system is used.

(ix) Crack path and fracture surface: tested specimen photos showing fracture surfaces on both sides and crack path side view; Mark at “embrittled zone tip” and “arrest” positions.

- Judgment for crack path requirement.

- Judgment for cleavage trigger location (whether side groove edge or V-notch edge).

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(x) Embrittled zone information:

When EBW is used: $L_{EB\text{-}s1}$, $L_{EB\text{-}s2}$ and $L_{EB\text{-}min}$

- Judgement for shear lip thickness requirement

- Judgment whether brittle fracture appearance area continues from the EBW front line

- Judgement for EBW defects requirement

- Judgement for EBW lengths, $L_{EB\text{-}s1}$, $L_{EB\text{-}s2}$ *and* $L_{EB\text{-}min}$ requirements

When LTG is used: $L_{LTG}$

- Judgment for shear lip thickness requirement

Test results:

When the specimen did not break into two pieces after brittle crack trigger, arrested crack length $a_{arrest}$

When the specimen broke into two pieces after brittle crack trigger,

- judgement whether brittle crack re-initiation or not.

If so, arrested crack length $a_{arrest}$:

- Judgement for $a_{arrest}$ in the valid range ($0.3W < a_{arrest} \leq 0.7W$)

- Final judgement either “arrest”, “propagate” or “invalid”

(xi) Dynamic measurement results: History of crack propagation velocity, and strain change at pin chucks, if needed

## 10 Use of test for material qualification testing

Where required, the method can also be used for determining the lowest temperature at which a steel can arrest a running brittle crack (the determined CAT) as the material property characteristic in accordance with 8.3.

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