TECHNICAL
REPORT

**ISO/TR
17641-3**

First edition
2005-03-15

Destructive tests on welds in metallic materials — Hot cracking tests for weldments — Arc welding processes —

Part 3:
Externally loaded tests

Essais destructifs des soudures sur matériaux métalliques — Essais de fissuration à chaud des assemblages soudés — Procédés de soudage à l'arc —

Partie 3: Essais sur éprouvette soumise à une charge extérieure

Reference number
ISO/TR 17641-3:2005(E)

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Foreword

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In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

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ISO/TR 17641-3 was prepared by the European Committee for Standardization (CEN) in collaboration with Technical Committee ISO/TC 44, *Welding and allied processes*, Subcommittee SC 5, *Testing and inspection of welds*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Throughout the text of this document, read “...this CEN Report...” to mean “...this Technical Report...”.

ISO 17641 consists of the following parts, under the general title *Destructive tests on welds in metallic materials — Hot cracking tests for weldments — Arc welding processes*:

— *Part 1: General*

— *Part 2: Self-restraint tests*

— *Part 3: Externally loaded tests* [Technical Report]

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Foreword

This document (CEN ISO/TR 17641-3:2005) has been prepared by Technical Committee CEN/TC 121 “Welding”, the secretariat of which is held by DIN, in collaboration with Technical Committee ISO/TC 44 “Welding and allied processes”.

1 Scope

This document outlines the test methods and procedures for carrying out externally loaded tests to assess susceptibility to hot cracking.

The following tests are described:

- Hot tensile tests
- Varestraint and Transvarestraint test
- Flat tensile test.

The above tests can provide information about the hot cracking sensitivity of parent materials, weld metals and weldments. Assessment is based upon the measurement of the "brittle temperature range" (BTR) where hot cracks occur.

This document applies primarily to austenitic stainless steels, nickel, nickel base and nickel copper alloys, weldments and welding consumables. However, the principles can be extended to other materials such as aluminium alloys and high strength steels by agreement between contracting parties.

2 Normative references

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

EN ISO 17641-1:2004, *Destructive tests on welds in metallic materials — Hot cracking tests for weldments – Arc welding processes — Part 1: General (ISO 17641-1:2004)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN ISO 17641-1:2004 apply.

4 Symbols, designations and units

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

Table 1 — Designation and symbols

Symbol	Designation	Unit
Hot tensile test		
BTR	Brittle temperature range, i.e. difference between NST and DTR (see Figure 2)	°C
DRR	Ductility recovery rate, difference (2—3)/(1—3) × 100 (see Figure 2)	%
DRT	Ductility recovery temperature, i.e. temperature at 5% reduction in area measured during "on cooling" tensile test	°C
NDR	Nil ductility temperature range, distance (4—6 see Figure 2)	°C
NST	Nil strength temperature, i.e. peak temperature of the test (See Figure 2, Point 6)	°C
RDR	Ratio of ductility recovery, area (2—3—4)/area (1—3—5) × 100 (See Figure 2)	-
R_m	Ultimate tensile strength	MPa
Z	Reduction in area	%
T_s	Solidus temperature (See Figure 2, Point 7)	°C
Varestraint- and Transvarestraint test		
L_{tot}	Total length of all detected hot cracks	mm
l	Specimen length	mm
R	Radius of the former	mm
t	Specimen thickness	mm
w	Specimen width	mm
Flat tensile test		
S_s	Specimen strain	%
S_v	Strain rate	mm/s
V_{crit}	Critical strain to form the first hot crack	mm/s
W_s	Welding speed	cm/min

5 Principle

Externally loaded hot cracking tests may be used to provide quantitative information on solidification, liquation and ductility dip cracking in accordance with Table 2. They are suitable for assessing the susceptibility to hot cracking of parent materials, weldments and weld metals. However it should be recognised that the exact mechanisms of the various forms of hot cracking are not fully understood. The different externally loaded tests described in this document use different criteria for the assessment of susceptibility to hot cracking. None of the tests reproduce exactly the conditions of temperature, cooling rate, restraint and externally applied strains, which occur in a wide range of fabrications where hot cracking may be considered to be a potential problem. Although work continues to address these issues, the tests in their presently developed form can only be used to rank materials, welding consumables and welding conditions. The results can then be compared with databases of relevant experience to make judgements as to potential suitability. For this reason it is not possible to state that any particular test is the most appropriate for any specific requirement. The user of the test shall decide on the basis of past experience, or on preliminary experiments, which is the most appropriate test for the required application.

Four types of hot cracking test are described and their relevance to the various forms of hot cracking, and their possible range of application, are summarised in Table 2.

All the hot cracking tests described depend on the imposition of an external load on the specimen using suitable test equipment.

This external loading can produce a measurable strain and strain rate on the specimen during the brittle temperature range (BTR) and can therefore reproduce certain aspects of the welding process. The results produced from this test are quantitative and are generally reproducible for the same test using a defined testing procedure and similar equipment.

Unfortunately, equipment and testing procedures are not standardised between different laboratories, and absolute reproducibility between laboratories is limited. Repeatability of results within a single laboratory using consistent procedures and the same equipment is generally good.

When parent materials are to be tested, the test specimen is heated either with a TIG melt run in the case of the Varestraint and flat tensile test or by resistance heating in the hot tensile test. In both cases a HAZ is formed which is subjected to straining and hence assessment of susceptibility to cracking.

When weld metal is to be tested, a weld deposit is made by the appropriate arc welding process and in the cases of the Varestraint and flat tensile test, is subjected to straining as the weld solidifies. Any cracking, which occurs, forms the basis of the assessment. For the hot tensile test the specimen is extracted from a multipass welded joint and assessment is based on measured mechanical properties using the appropriate procedure, see 6.1.1

Multipass welds can also be assessed using the Varestaint and flat tensile test, but for these tests, samples with multipass deposits have to be prepared and the weld metal is then reheated using a similar TIG melt run to that utilised in parent material tests.

Table 2 — Hot cracking tests, types of cracking and applications

Type of test	Type of cracking	Results	Applications
Varestraint	Solidification	L_{tot} BTR	Parent material, selection and approval.
	Liquation	L_{tot}	Weld metal, selection and approval.
	Ductility Dip	L_{tot}	Welding procedures
Transvarestraint	Solidification	L_{tot}	Weld metal selection Welding procedures
Flat tensile type (PVR test)	Solidification	V_{crit}	Material selection,
	Liquation	V_{crit}	Multipass weldments
	Ductility Dip	V_{crit}	Welding procedures Material combinations
Hot tensile test (Gleeble ^{TM})	Solidification	BTR	Material selection and approval
	Liquation	BTR	

Although it is possible for more than one form of hot cracking to be present in a given test piece it should be noted that the formation of one type of cracking e.g. solidification, may relieve the test strain on the specimen to such an extent that other forms of cracking do not occur. Therefore the lack of a particular form of cracking in the testpiece, does not mean that there is no risk of that type of cracking occurring in practice.

The Transvarestraint test was primarily designed to assess weld metal solidification cracking by applying strains transverse to the length of the weld. It is possible that other types of hot cracking form and if these do occur, they should be noted on the test report.

6 Description of the tests

6.1 Hot tensile test

6.1.1 General

The hot tensile test determines the hot cracking susceptibility of a material in a simulated welding thermal cycle using a cylindrical shaped tensile specimen. The specimen can be abruptly broken at any convenient moment in the welding thermal cycle. For the study of hot cracking where it is necessary to simulate fusion welding thermal heating, a specimen shall be heated to its melting temperature. A number of cylindrical tensile test specimens are used, which can be loaded to failure at a predefined point (Procedure A).

To simulate the HAZ thermal history and liquation cracking, the specimen is heated only as far as the nil strength temperature (NST) rather than the melting point. This procedure is the same for both liquation cracking in the HAZ of parent materials and the interrun HAZ's of multipass welds (Procedure B). The test procedures are primarily used in weld metal hot cracking studies. The tests are characterised by good reproducibility.

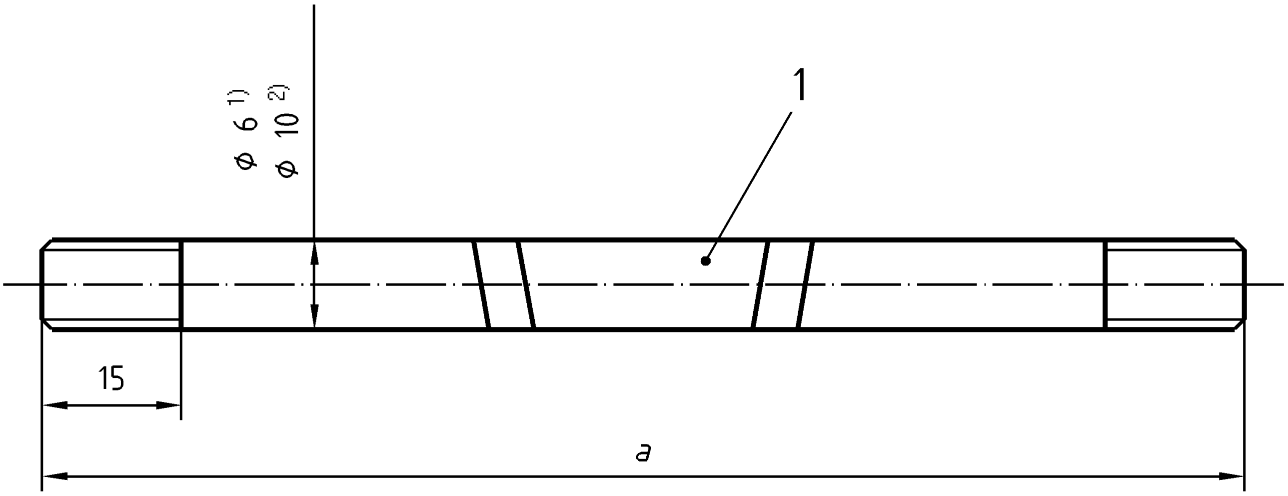
6.1.2 Specimen size

Procedure A — to simulate solidification cracking and heating to the melting point, a specimen of length 130 mm and diameter 10 mm should be used.

Procedure B — to simulate HAZ liquation cracking and to determine the NST, a specimen of length 110 mm and diameter 6 mm should be used.

The specimen dimension together with the location of the weld joint are shown in Figure 1.

Dimensions in millimetres



Key

1 Weld metal
a = 130 for solidification cracking
110 for liquation cracking

[1] for liquation cracking
[2] for solidification cracking

Figure 1 — Specimen dimensions for the hot tensile test

6.1.3 Protective atmosphere

The test specimens shall be heated in a chamber, which is first evacuated and then back-filled with Argon to prevent excessive oxidation at high temperature. Any suitable means of back filling can be used, provided the oxygen content of the atmosphere at the start of the test does not exceed 0,1 %.

6.1.4 Test procedure

6.1.4.1 General

Temperature measurement of the specimen should be carried out by percussion welding a 0,2/0,25mm diameter Pt-PtRh thermocouple fixed to middle of the specimen length and perpendicular to the diameter of the specimen.

6.1.4.2 Procedure A — Solidification cracking studies

The 10 mm diameter specimen is mounted in water cooled copper jaws and then heated to the melting point using controlled resistance heating. The central portion of the specimen is prevented from collapse, as it nears the melting point, by a close-fitting quartz tube. During solidification and on further cooling the jaws are held fixed so that the shrinkage strains/restraint can induce cracking.

In subsequent tests, controlled compression can be superimposed after the heating cycle to establish the strain necessary to avoid cracking.

6.1.4.3 Procedure B — Liquation cracking studies

To determine the peak nil strength temperature (NST), the 6 mm diameter specimen should be heated to between 50 °C and 100 °C below the solidus temperature at heating rate of approximately 50 °C/s (and up to 250 °C/s for some alloys). At this stage the heating rate should be reduced to about 2 °C/s until the specimen breaks under a constant load of approximately 100 N. The hot ductility can be determined using on-heating and on-cooling tests. For the on-cooling tests the specimen shall be heated to the NST and then cooled to the test temperature in order to conduct the tensile test.

For on-heating tests the specimen need only be heated to the test temperature and then subjected to the tensile loading at a strain rate of 50 mm/s. Heating and cooling rates should correspond to the weld metal thermal cycle being simulated.

During heating, free expansion of the specimen should be permitted. However, if data is available from a real situation, using the equipment programmes can simulate then welding strains. During cooling, free shrinkage of the specimen should be permitted or, alternatively, a controlled compression can be applied until the ductility recovery temperature (DRT) is reached.

This compensates for the specimen contraction in the axial direction and can be used to provide a quantitative measurement of strains necessary to prevent cracking in the specimen. A minimum of 12 specimens is usually required to establish a reliable hot ductility curve.

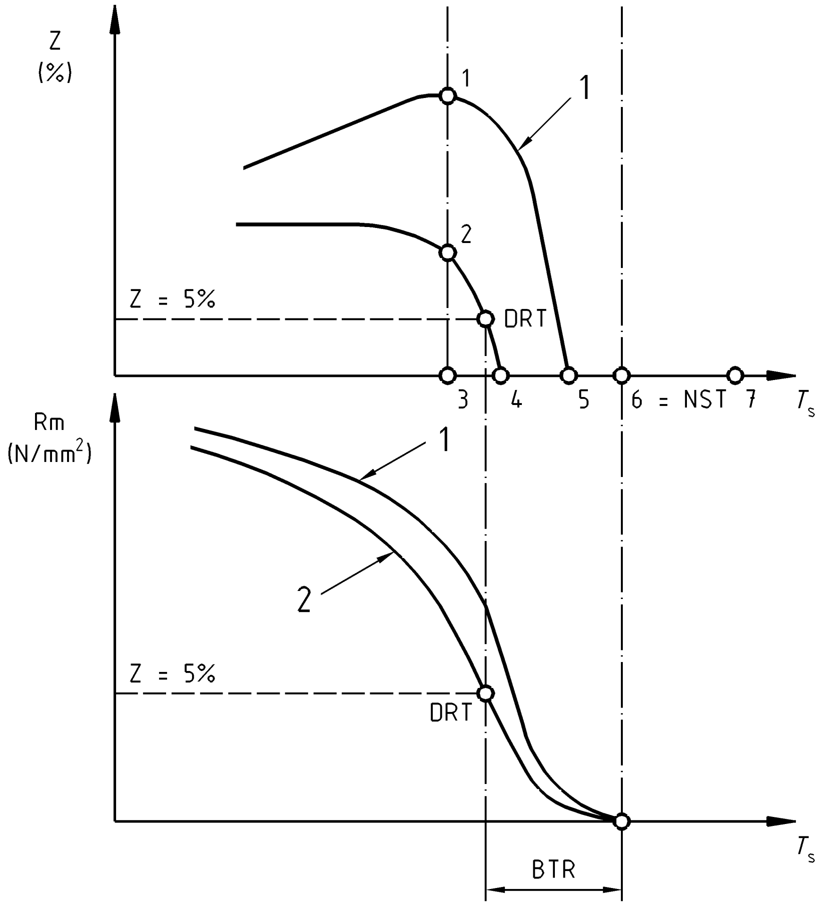
6.1.5 Test results

After testing, the reduction in area (Z) shall be calculated from the fractured cross sectional area as a fraction of the original cross section of the test specimen. The ultimate tensile strength (R_m) can be obtained by dividing the maximum force by the initial cross-sectional area of the specimen. This ultimate tensile strength and the reduction of area should be plotted for both on-heating and on-cooling tests as a function of test temperature. Typical plots are shown in Figure 2.

The material is considered to be susceptible to hot cracking whilst it is in the brittle temperature range (BTR) and this is defined as the difference between the nil strength temperature (NST) and the ductility recovery temperature (DRT). For the purpose of comparing materials, the DRT is defined as the temperature at which the reduction of area in an on-cooling test reaches 5 %.

The susceptibility to liquation cracking of a material can be characterised by the ratio of ductility recovery (RDR), the ductility recovery rate (DRR), and the nil ductility temperature range (NDR) — see Table 1.

The most reliable criterion is the ratio of ductility recovery (RDR), and can be used to predict base metal HAZ hot cracking behaviour.



Key

1 On heating
2 On cooling

Figure 2 — Results presentation

6.2 Principles of the Varestraint and Transvarestraint tests

6.2.1 General principles

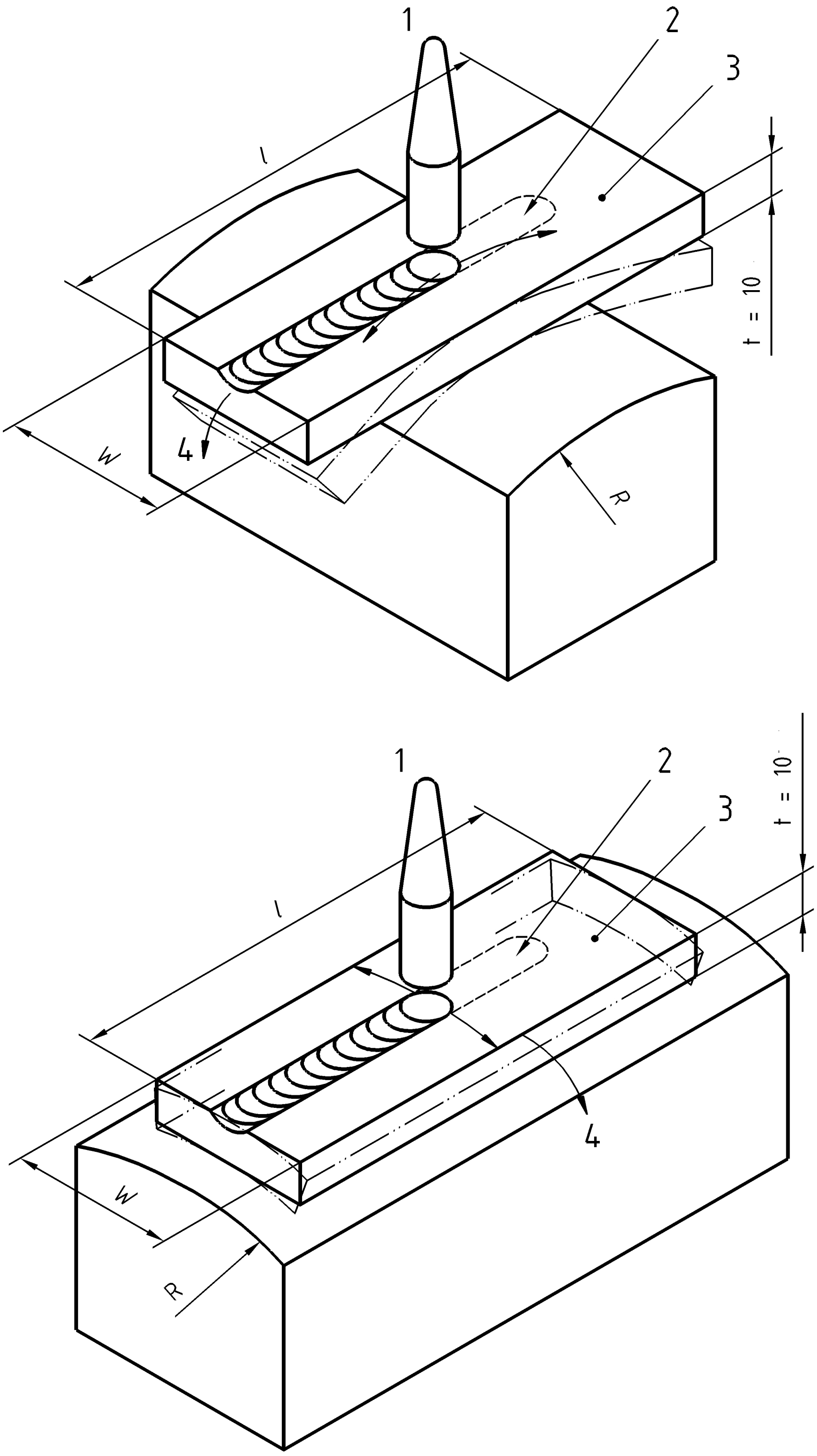
The Varestraint and Transvarestraint tests can be used to provide a measure of the hot cracking susceptibility of parent materials, filler materials and weldments by simultaneously depositing a weld bead and applying a test strain. In the Varestraint test the load is applied in the longitudinal direction of the weld bead under test. It is capable of producing all three types of hot cracking - namely, solidification, liquation and ductility dip (see Table 2).

In the Transvarestraint test the load is applied transverse to the direction of the weld bead under test, and is primarily designed to assess susceptibility to solidification cracking. The material strained in the tests may be a parent metal, or a previously deposited weld metal, remelted by a TIG run or weld metal deposited during a test.

Figure 3 shows the general principles of the test methods. It should be noted that specialised equipment is required to apply the strains onto the specimen and to synchronise the straining and welding operations. Although a number of laboratories worldwide have suitable equipment for these tests, there are significant differences in the equipment between laboratories and for this reason, reproducibility of results between laboratories may be rather poor. However, within a single laboratory the test(s) can be used to rank materials and to make comparisons with materials of known susceptibility in practical situations.

The claimed advantages of the test are rapid testing and evaluation of results, combined with low scatter of results and good reproducibility (with a single testing machine). The test is capable of discriminating between small changes in test material composition and/or welding conditions. Useful data can be generated from a small number of tests under a given set of conditions (typically 1 to 3).

Dimensions in millimetres



Key

1 Torch position at bending
2 Welding stop
3 Specimen
4 Variable controlled bending speed by hydraulic system

Figure 3 — Principle of Varestraint (up) /Transvarestraint tests (down)

6.2.2 Specimen size

Specimen size is not fixed and is dependent on the material available for testing, the exact nature of the test and the loading capacity of the test machine.

- - Varestraint test

  The most common form of specimen is a simple flat bar with:
  - a length (l) of between 80 mm and 300 mm
  - a width (w) of between 40 mm and 100 mm

  and

  - a thickness (t) dependent on the material being tested and the loading capacity of the test machine.
- - Transvarestraint test

  Typical specimen dimensions are:
  - length (l) 100 mm
  - width (w) 40 mm

  and
  - thickness (t) 10 mm.

NOTE However, specimen dimensions can be modified to enable both longitudinal and transverse welds to be tested in addition to thin sheet materials and pipes.

6.2.3 Test procedure

Performance of the tests in their standard form involves the production of a TIG melt run on parent material or previously deposited weld metal.

Welding parameters can be chosen to suit particular applications, but the standard conditions are:

- 12,5 V, 85 A, 18 cm/min travel speed (low heat input);
- 13,5 V, 205 A, 11 cm/min travel speed (high heat input).

Welding parameters used should be recorded.

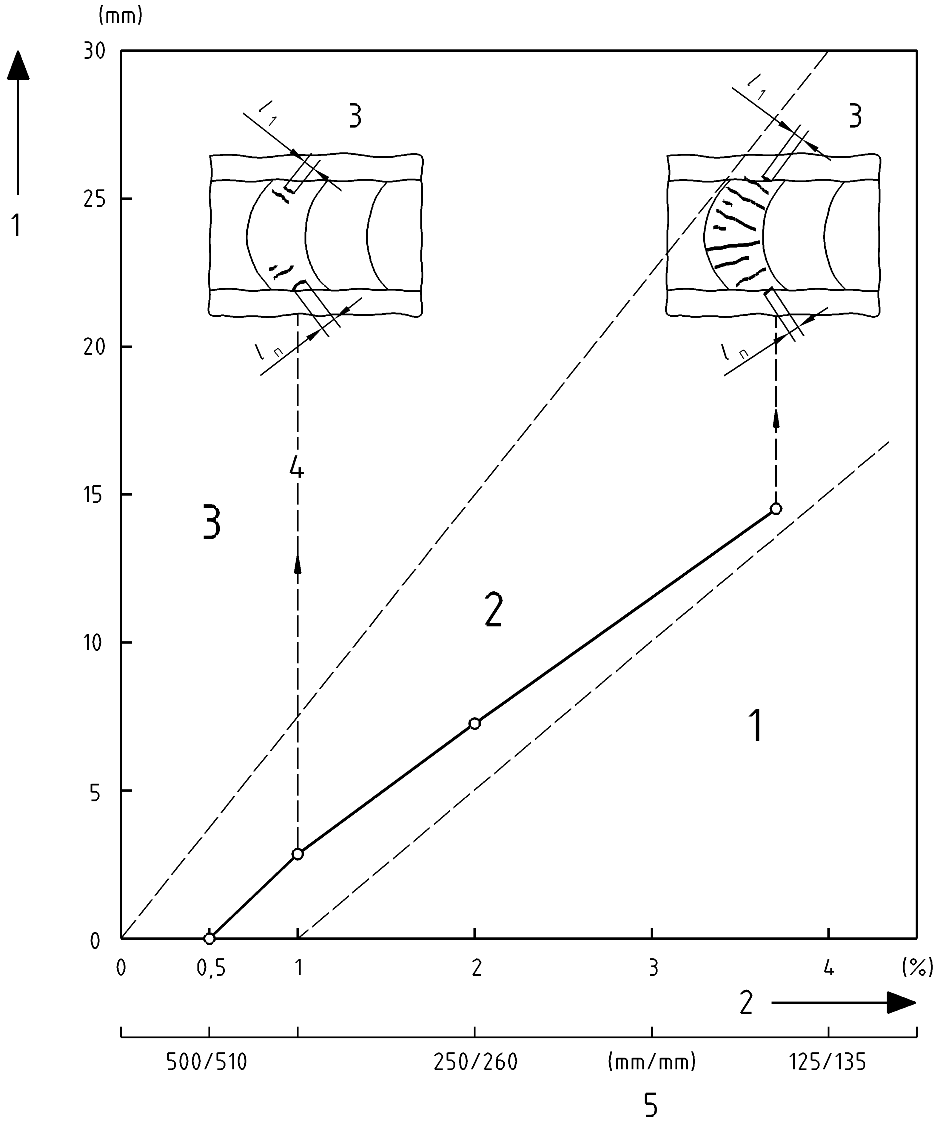
At a fixed point in the TIG melt run, usually the centre of the specimen, deformation of the specimen takes place by bending over a pre-shaped former (Figure 3). The loading is usually applied by hydraulic ram/s at a controlled speed which should exceed 1,8 mm/s. The loading sequence is automatically synchronised with the welding operation.

6.2.4 Test results

On completion of each test, the specimen should be visually examined for cracks at a magnification of ×25. The total length of all visible cracks (L_{tot}) should be determined and plotted as a function of the bending strain. The relative position of the crack length/surface strain curve can enable an assessment of susceptibility to hot cracking to be carried out (see Figure 4).

Although the results shown as an example in Figure 4 apply to the Varestraint test, similar diagrams can be constructed for the Transvarestraint test by plotting total crack length against surface bending strain. The presentation of the results in Figure 4 is simply a representation of how the data might be assessed, in relation to known welding behaviour. The three areas indicating ‘weldable’, ‘restricted weldability’ and ‘not weldable’ are shown purely as an illustration and are not intended to indicate any absolute assessment of weldability or sensitivity to hot cracking.

Since it is extremely difficult, if not impossible to relate the strains imposed during the test, to those that might be experienced by a welded joint in a real life fabrication, it is strongly recommended that the tests be used to compare new materials or welds with those of known performance in real life situations.



Key

1 Total crack length
2 Radius former/plunger
3 Varestraint specimen
4 Measurement of length: Stereomicroscope, 25 fold: $L_{tot} = l_1 + l_2 + ... + l_n$
5 Welding speed
Field 1 resistant to hot cracking
Field 2 increasing risk of hot cracking
Field 3 high risk of hot cracking

Figure 4 — Typical presentation of results for The Varestraint and Transvarestraint tests

6.3 Flat tensile test

6.3.1 General

The flat tensile test (for example Programmable Deformation Cracking Test) is capable of quantifying the hot cracking susceptibility of base metals, weld metals and a range of welding procedures.

This hot cracking test is carried out by the use of a single flat tensile test specimen, which is strained in a horizontal tensile test equipment programmed with a linearly increasing tension speed. The PVR test (Programmable deformation test) procedure differs from that of the Varestraint and Transvarestraint tests in the fact that a programmable deformation by a linearly increasing tension speed is imposed during the deposition of a weld run in the same direction as the weld run. In principle, the test can be carried out with or without filler materials.

Parent materials can be assessed using a TIG melt run with standardised welding parameters.

Filler materials can be assessed using weld conditions recommended by the consumable manufacturer or actual welding conditions can be applied to reproduce a practical situation.

The welding procedure can be optimised by variation of welding conditions (e.g. welding parameters, type of consumable, shielding gas mixtures, flux-wire-compositions etc). in order to minimise the risk of hot cracking.

All three types of hot cracking (solidification, liquation, ductility dip) can be reproduced in a single test dependent upon the material susceptibility.

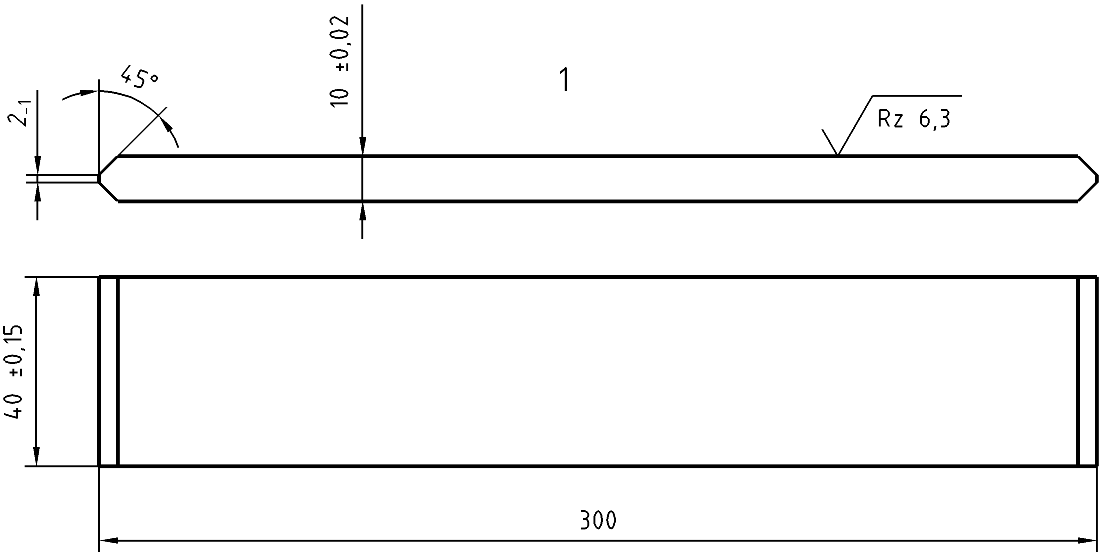
In principle, only a single test is required to establish the hot cracking sensitivity of a base metal or weld metal provided that reference data is available for comparison.

It is claimed that the test is reproducible with low scatter and is capable of good discrimination between the three main types of hot cracking.

6.3.2 Specimen size

The exact size of the flat tensile specimen is determined by the capacity of the testing machine. The most commonly used dimensions are (40 × 10 × 300) mm (width × thickness × length), as shown in Figure 5. The specimen surface should be prepared by machining and grinding in the longitudinal direction to a finish of 6,3 µm or better. Surface marks perpendicular to the direction of welding, which might initiate spurious cracks, should be avoided. The flat tensile specimen is then welded into a special fixture to ensure the programmable deformation in the tensile test equipment.

Dimensions in millimetres



Key

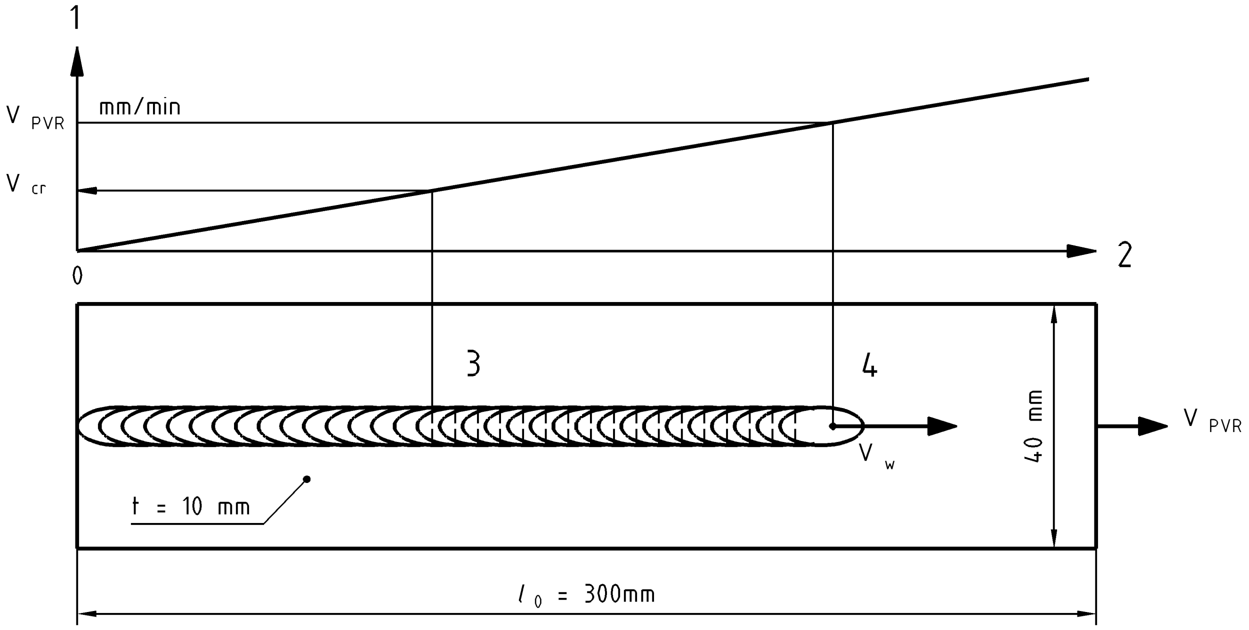
1 Surface is sharpened lengthways

Figure 5 — Programmable Deformation Cracking Test (PVR-Test) — Test piece dimension

6.3.3 Test procedure

The test procedure in its standard form is shown in Figure 6. The welding procedure (using a constant welding speed) is made in combination with a linearly increased tension speed v_{PVR} starting from zero and constantly accelerating to 70 mm/min, on completion of the test procedure. Although the standard form of the test is carried out with the weld parallel to the direction of straining, it is possible to evaluate welds perpendicular to the direction of straining.

On completion of the test, the weld run on the test specimen is examined by microscopy (enlarged 25×) to establish the critical tension speed v_{cr} corresponding to the appearance of the first hot crack, for each of the different hot cracking types (if more than one type is produced during the test).



Key

1 Linearly increased tension speed
2 Time, s
3 First hot crack
4 Welding speed

Figure 6 — Test procedure of Programmable Deformation Cracking Test (PVR-Test)

6.3.4 Test results

v_{cr} corresponds to the first onset of cracking. It is defined as that point where the first hot crack is detected visually at a magnification of ×25. This critical tension speed v_{cr} is used as the test criteria for the PVR-Test to quantify hot cracking susceptibility. It can be established for each of the hot crack types.

7 Test reports

Any assessment of hot cracking susceptibility should include the following information, as a minimum, in any test report:

a) reference to this document;

b) description of the test(s) being used;

c) description of base (parent) material and filler material, if any;

d) identification of the test piece/test specimens;

e) dimensions of the test piece/test specimens;

f) welding conditions used;

g) any special testing conditions;

h) test results (specific to the test carried out).

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