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

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

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Foreword

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

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see the following URL: www.iso.org/iso/foreword.html.

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

This second edition of ISO 15653 cancels and replaces the first edition (ISO 15653:2010), which has been technically revised.

The main changes compared to the previous edition are as follows:

— new formulae for the calculation of single-point determination of CTOD (12.2.2) have been added;

— introduction for reverse bending in C.3 has been added;

— assessment of pop-in in D.1 has been clarified;

— new formula for the calculation for single-point determination of CTOD in shallow notched specimens in E.4 has been added.

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

1 Scope

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

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

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12135:2016, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

3 Terms and definitions

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

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

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

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

3.2
target area
intended fatigue crack tip position within the *weld metal* (3.7) or *HAZ* (3.9)

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

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

Note 1 to entry: See Annex C.

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

Note 1 to entry: Filler metal, the melting temperature of which is of the same order as that of the parent metal, may or may not be used.

3.6
weld
union of pieces of metal made by *welding* (3.5)

3.7
weld metal
all metal melted during the making of a *weld* (3.6) and retained in the weld

3.8
parent metal
metal to be joined by *welding* (3.5)

3.9
heat-affected zone
HAZ
zone in the parent metal that is metallurgically affected by the heat of *welding* (3.5)

3.10
fusion line
FL
junction between the *weld metal* (3.7) and the *parent metal* (3.8) heat-affected zone

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

Note 1 to entry: See Figure A.1 for examples.

3.12
specific microstructure
SM
target microstructure for the fatigue crack tip

Note 1 to entry: See Figure A.2 for examples.

3.13
specimen blank
specimen prepared from *weld metal* (3.7) plus *parent metal* (3.8) prior to notching

3.14
post-weld heat treatment
heat treatment applied after *welding* (3.5) for the purpose of reducing residual stresses or modifying *weld* (3.6) properties

4 Symbols and units

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

Table 1 — Symbols and units

Symbol	Unit	Designation
d_1, d_2	mm	Lengths of microstructural features associated with pop-in.
h	mm	Effective weld width, defined as shortest distance between fatigue crack tip and weld fusion line within the central 75 % of the thickness (see Figures 13 and 14).
HV10		Vickers hardness using 10 kg force.
N		Normal to welding direction.
P		Parallel to welding direction.
Q		Weld thickness direction.
$R_{p0,2b}$	MPa	0,2 % offset yield strength of parent metal at the temperature of the fracture test.
$R_{p0,2w}$	MPa	0,2 % offset yield strength of weld metal at the temperature of the fracture test.
R_{mb}	MPa	Tensile strength of parent metal at the temperature of the fracture test.
R_{mw}	MPa	Tensile strength of weld metal at the temperature of the fracture test.
s_1	mm	Distance between crack tip and target area measured in the crack plane (see Figure 12).
s_2	mm	Distance between crack tip and target area measured perpendicular to the crack plane (see Figure 12).
V	mm	Crack mouth opening displacement at notch edge in bend specimen and that at load line in compact specimen.
V_g	mm	Displacement measured by clip gauge mounted on knife edges.
V_{g1}	mm	Displacement measured with the double clip gauge arrangement described in E.3 and illustrated in Figure E.1.
V_{g2}	mm	Displacement measured with the double clip gauge arrangement described in E.3 and illustrated in Figure E.1.
X		Direction parallel to primary grain flow of parent metal.
Y		Direction transverse to primary grain flow and to thickness of parent metal.
Z		Direction through thickness of parent metal.
Δa_{pop}	mm	Maximum length of brittle crack extension (beyond SZW; see 3.1) associated with pop-in.
λ	mm	Length of specific microstructure measured in pre-test or post-test metallography (see Figure B.2).

5 Principle

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

a) located in relation to a weld feature of interest, referred to as "weld positional" (WP), and

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

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

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

The fracture toughness test is performed and evaluated in accordance with ISO 12135, but subject to additional requirements of this test method regarding post-test analysis (see 12.2.1, 12.2.2 and 12.2.3) and qualification (see 12.3).

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

The sequence of operations is summarized in Figure 1.

6 Choice of specimen design, specimen orientation and notch location

6.1 Classification of target area for notching

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

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

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

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

6.2 Specimen design

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

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

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

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

6.3 Specimen and crack plane orientation

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

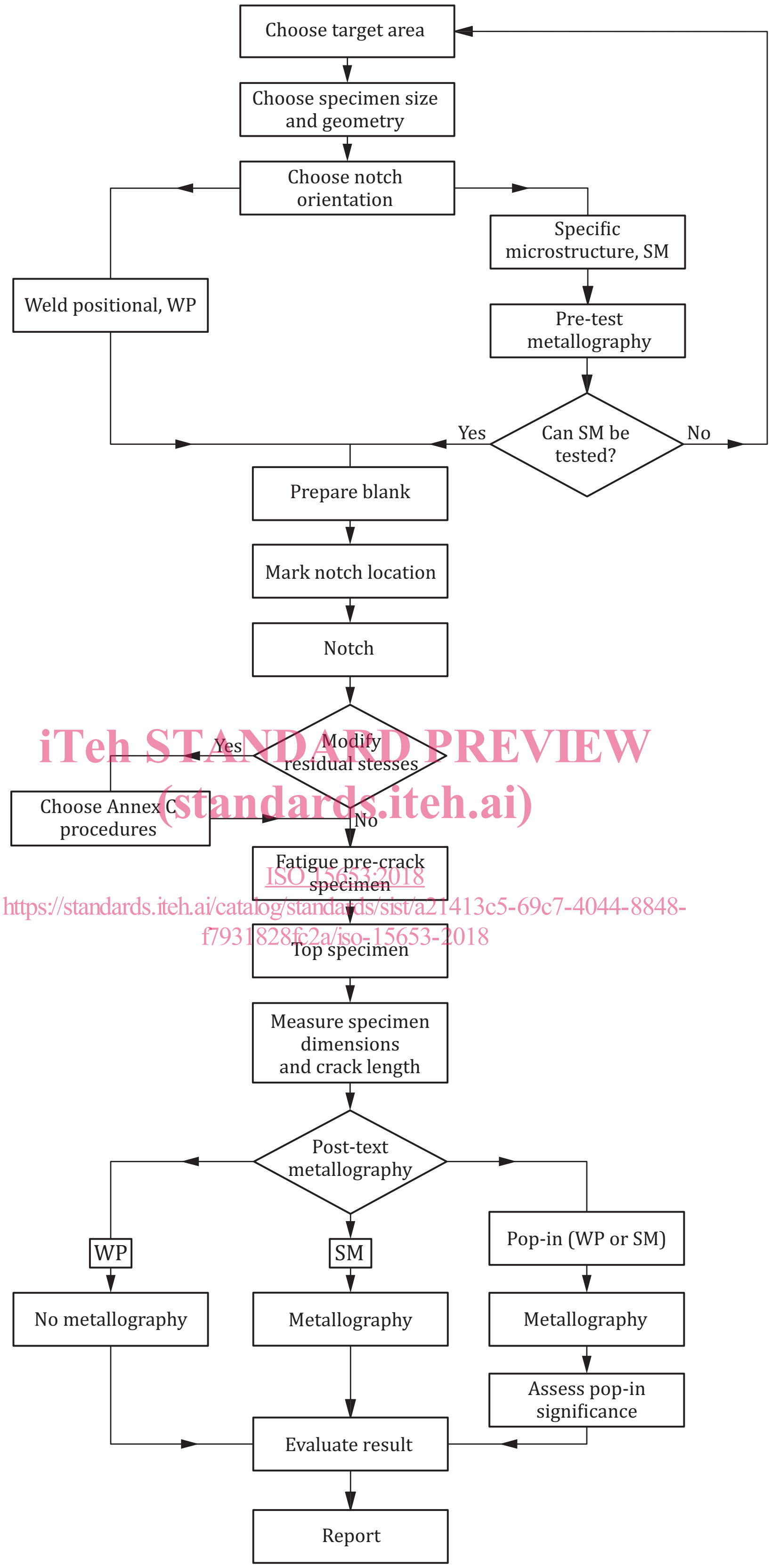
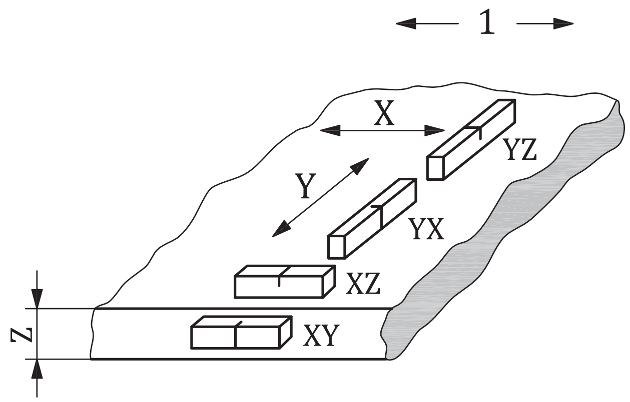
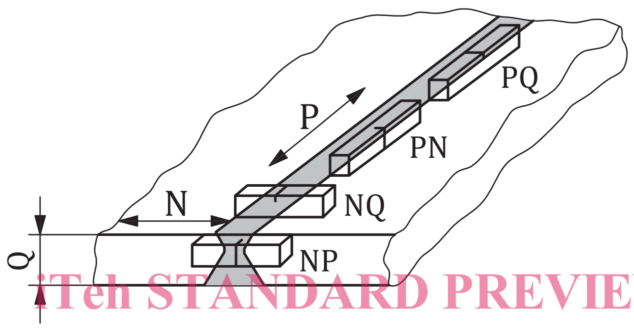


Figure 1 — Flow chart for testing



a) Parent metal



b) Weld metal

Key

1 rolling direction
N normal to weld direction
P parallel to weld direction
Q weld thickness direction

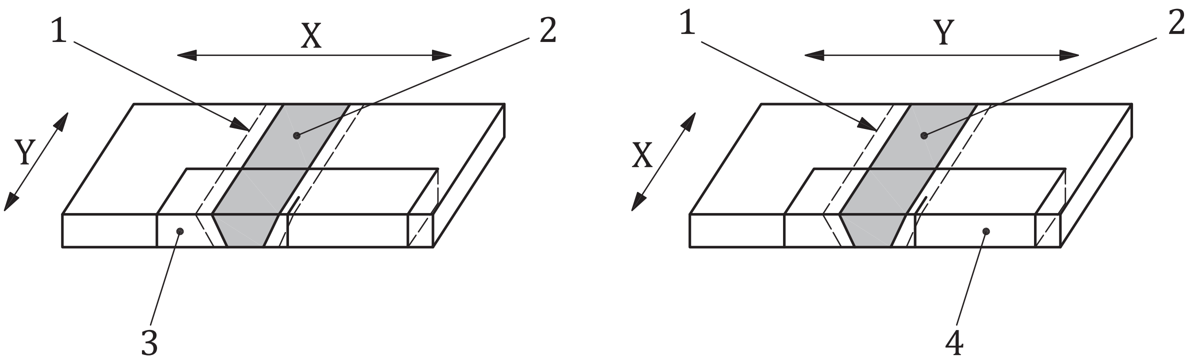
NOTE 1 The first letter in the designation is the direction normal to the crack plane.

NOTE 2 The second letter in the designation is the expected direction of crack propagation.

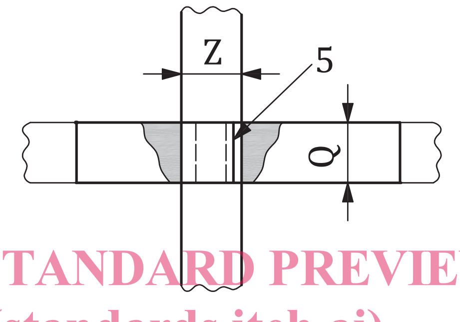
NOTE 3 See ISO 3785 for the definitions of X, Y and Z.

Figure 2 — Crack plane orientation codes for fracture toughness specimens of parent metal and weld metal

As shown in Figure 2, specimen orientations NP and PN shall be referred to as through-thickness notched, while specimen orientations NQ and PQ shall be referred to as surface-notched.



a) Typical butt weld



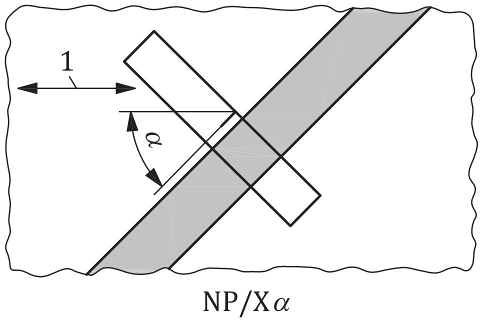
b) Cruciform joint

Key

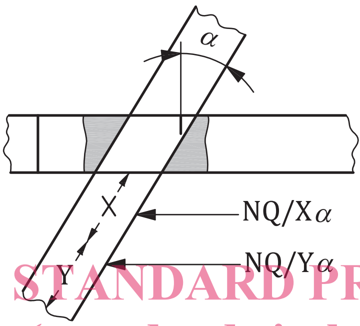
1 HAZ
2 weld
3 weld specimen orientation NP/XY
4 weld specimen orientation NP/YX
5 through-crack NP/ZX or NP/ZY
X rolling direction
Q weld thickness direction

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

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



a) Typical butt weld



b) Angled cruciform joint

Key

1 rolling direction

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

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

7 Pre-machining metallography

7.1 Microstructural assessment of macrosections

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

Examination of the macrosections shall be used to establish that

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

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

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

Owing to the lower crack tip constraint associated with a shallow notch, the fracture toughness value determined from a shallow-notched specimen ($0{,}10 \le a_0/W \le 0{,}45$) may be higher than that obtained from a standard notched specimen ($0{,}45 \le a_0/W \le 0{,}70$) for the same crack tip microstructure. The significance of this potential difference shall be considered when a shallow-notched specimen is to be used.

7.2 Additional requirements for heat-affected zone tests

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

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

Where surface-notched specimens are selected, the macrosection shall be used to confirm that the target microstructure is present within the range $0{,}45 \le a_0/W \le 0{,}70$.

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

8 Machining

8.1 Tolerances on specimen dimensions

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

Compact specimens shall meet the dimensional requirements of ISO 12135. Standard bend specimens shall conform to Figure 5. Shallow-notched bend specimens (see 7.1, 7.2 and Annex E) shall likewise conform to Figure 5, except that the relative crack length shall be in the range $0{,}10 \le a_0/W \le 0{,}45$.

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

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

When it is not possible to straighten a specimen blank taken from pipe, a rectangular block of test material may be cut from the pipe and joined by welding to suitable extension pieces. The total length of the test block and extension pieces shall give a specimen of sufficient length to satisfy the curvature