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Non-destructive testing of welds — Ultrasonic testing — Use of time-of-flight diffraction technique (TOFD)

Essais non destructifs des assemblages soudés — Contrôle par ultrasons — Utilisation de la technique de diffraction des temps de vol (TOFD)

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Foreword

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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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of 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 www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 44, *Welding and allied processes*, Subcommittee SC 5, *Testing and inspection of welds*.

This second edition cancels and replaces the first edition (ISO 10863:2011), which has been technically revised.

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

— the whole document has been updated to the state of the art; ISO 22232 series has been taken into account;

— Clause 3 has been updated;

— Figure 1 to Figure 6 have been added;

— Figure B.1 to Figure B.18 have been updated.

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

Official interpretations of ISO/TC 44 documents, where they exist, are available from this page: https://committee.iso.org/sites/tc44/home/interpretation.html.

Non-destructive testing of welds — Ultrasonic testing — Use of time-of-flight diffraction technique (TOFD)

1 Scope

This document specifies the application of the time-of-flight diffraction (TOFD) technique to the semi- or fully automated ultrasonic testing of fusion-welded joints in metallic materials of minimum thickness 6 mm.

It applies to full penetration welded joints of simple geometry in plates, pipes, and vessels, where both the weld and the parent material are low-alloyed carbon steel. Where specified and appropriate, TOFD can also be used on other types of materials that exhibit low ultrasonic attenuation (especially that due to scatter).

Where material-dependent ultrasonic parameters are specified in this document, they are based on steels having a sound velocity of (5 920 ± 50) m/s for longitudinal waves and (3 255 ± 30) m/s for transverse waves. It is necessary to take this fact into account when testing materials with a different velocity.

This document makes reference to ISO 16828 and provides guidance on the specific capabilities and limitations of TOFD for the detection, location, sizing and characterization of discontinuities in fusion-welded joints. TOFD can be used as a stand-alone method or in combination with other non-destructive testing (NDT) methods or techniques, for manufacturing inspection, and for in-service inspection.

This document specifies four testing levels (A, B, C, D) in accordance with ISO 17635 and corresponding to an increasing level of testing reliability. Guidance on the selection of testing levels is provided.

This document permits assessment of TOFD indications for acceptance purposes. This assessment is based on the evaluation of transmitted, reflected and diffracted ultrasonic signals within a generated TOFD image.

This document does not include acceptance levels for discontinuities.

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 5577, *Non-destructive testing — Ultrasonic testing — Vocabulary*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO 16828, *Non-destructive testing — Ultrasonic testing — Time-of-flight diffraction technique as a method for detection and sizing of discontinuities*

ISO 17640, *Non-destructive testing of welds — Ultrasonic testing — Techniques, testing levels, and assessment*

ISO 22232-1[1)], *Non-destructive testing — Characterization and verification of ultrasonic test equipment — Part 1: Instruments*

1) Under preparation. (Preparation at the time of publication: ISO/FDIS 22232-1.)

ISO 22232-2[2)], *Non-destructive testing — Characterization and verification of ultrasonic test equipment — Part 2: Probes*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5577 and the following apply.

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

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

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

3.1
time-of-flight diffraction image
TOFD image
two-dimensional image, constructed by collecting adjacent A-scans while moving the *time-of-flight diffraction setup* (3.3)

Note 1 to entry: The signal amplitude of the A-scans is typically represented by grey-scale values.

3.2
time-of-flight diffraction indication
TOFD indication
pattern or disturbance in the *time-of-flight diffraction image* (3.1) which can need further evaluation

3.3
time-of-flight diffraction setup
TOFD setup
probe arrangement defined by probe characteristics (e.g. frequency, probe element size, beam angle, wave mode) and *probe centre separation* (3.6)

3.4
beam intersection point
point of intersection of the two main beam axes

3.5
lateral wave
longitudinal wave traveling the shortest path from transmitter probe to receiver probe

3.6
probe centre separation
PCS
distance between the index points of the two probes

Note 1 to entry: The PCS for two probes located on a curved surface is the straight-line, geometric separation between the two probe index points and not the distance measured along the surface.

3.7
offset scan
scan parallel to the weld axis, where the *beam intersection point* (3.4) is not on the centreline of the weld

4 General remarks on the capabilities of the technique

General principles of the TOFD technique are described in ISO 16828. For the testing of fusion-welded joints, some specific capabilities and limitations of the technique shall be considered.

2) Under preparation. (Preparation at the time of publication: ISO/DIS 22232-2.)

The TOFD technique is an ultrasonic image-generating technique, which offers the capability of detection, location, and sizing. To a certain extent, characterization of discontinuities in the weld material as well as in the adjacent parent material is also possible.

Compared with purely reflection-based techniques, the TOFD technique, which is based on diffraction as well as reflection, is less sensitive to the orientation of the discontinuity. Discontinuities oriented perpendicular to the surface, and at intermediate angles of tilt, are detectable as well as discontinuities in the weld fusion faces.

In certain circumstances (e.g. thickness, weld preparation, scope of testing) more than one single TOFD setup is required.

A typical TOFD image is linear in time (vertical axis) and probe movement (horizontal axis). Because of the V-configuration of the ultrasound paths, the location of a possible discontinuity is then non-linear. TOFD testing shall be carried out in a correct and consistent way, such that valid images are generated which can be evaluated correctly, e.g. coupling losses and data acquisition errors shall be avoided, see 12.2.

The interpretation of TOFD images requires skilled and experienced operators. Some typical TOFD images of discontinuities in fusion-welded joints are provided in Annex B.

There is a reduced capability for the detection of discontinuities close to or connected with the scanning surface or with the opposite surface. This shall be considered especially for crack-sensitive steels or at in-service inspections. In cases where full coverage of these zones is required, additional measures shall be taken, e.g. TOFD can be accompanied by other NDT methods or techniques.

Diffracted signals from weld discontinuities can have small amplitude responses. The grain scatter effect from coarse-grained material can hinder the detection and evaluation of such responses. This shall be taken into account whenever testing such material.

5 Testing levels

This document specifies four testing levels (A, B, C and D, see Table 1). From testing level A to testing level C an increasing reliability is achieved.

Table 1 — Testing levels

Testing level	TOFD setup	Reference block for setup verification (see 8.2)	Reference block for sensitivity settings (see 10.1.4)	Offset scan	Written test procedure
A	As in Table 2	No	No	No	This document
B	As in Table 2	No	Yes	No	This document
C	As in Table 2	Yes	Yes	a	Yes
D	As defined by specification	Yes	Yes	a	Yes

[a] The necessity, number and position of offset scans shall be determined.

If the specified acceptance level requires detection of a certain discontinuity size at both surfaces or one surface of the weld (see Clause 4), this can necessitate the use of techniques or methods outside the scope of this document.

For manufacturing inspections (see also ISO 17635), all testing levels are applicable. Level A is only applicable for wall thicknesses up to 50 mm. For in-service inspections, only testing level D shall be applied.

6 Information required prior to testing

6.1 Items to be defined by specification

Information on the following items is required:

a) purpose and extent of TOFD testing (see Clause 5 and Clause 8);

b) testing levels (see Clause 5), e.g.:

   1) whether a written test procedure is required,

   2) whether reference blocks are required;

c) specification of reference blocks, if required (see 10.3);

d) manufacturing or operation stage at which the testing is to be carried out;

e) requirements for: temperature, access and surface conditions (see Clause 8);

f) reporting requirements (see Clause 13);

g) acceptance criteria;

h) personnel qualifications (see 7.1).

6.2 Specific information required by the operator before testing

Before any testing of a welded joint can begin, the operator shall have access to all the information as specified in 6.1 together with the following additional information:

a) written test instruction or procedure (see 6.3), if required;

b) type(s) of parent material and product form (i.e. cast, forged, rolled);

c) joint preparation and dimensions;

d) welding procedure or relevant information on the welding process;

e) time of testing relative to any post-weld heat treatment;

f) result of any parent metal testing carried out prior to and/or after welding;

g) discontinuity type and morphology to be detected.

6.3 Written test instruction or procedure

For testing levels A and B, this document satisfies the need for a written test procedure.

For testing levels C and D, or where the techniques described in this document are not applicable to the welded joint to be tested, a specific written test procedure shall be used.

When data collection is performed by personnel qualified to Level 1 according to ISO 9712, a written test instruction shall be prepared. The written test instruction shall contain as a minimum the information listed in Clause 13.

7 Requirements for test personnel and test equipment

7.1 Personnel qualifications

In addition to a general knowledge of ultrasonic weld testing, all personnel shall be competent in the TOFD technique. Documented evidence of their competence (level of training and experience) is required.

Preparation of written test instructions, final off-line analysis of data, and acceptance of the report shall be performed by personnel qualified as a minimum to Level 2 in accordance with ISO 9712 or equivalent in ultrasonic testing in the relevant industrial sector. In accordance with a written instruction and under the supervision of Level 2 or Level 3 personnel, equipment setup, data acquisition, data storage, and report preparation can be performed by personnel qualified to a minimum of Level 1 in accordance with ISO 9712 or equivalent in ultrasonic testing in the relevant industrial sector.

For data acquisition, the Level 1 personnel may be supported by an assistant technician.

In cases where the above minimum qualifications are not considered adequate, job-specific training shall be carried out.

7.2 Test equipment

7.2.1 Ultrasonic instrument

The ultrasonic instrument used for the TOFD technique shall comply with the requirements of ISO 22232-1, where applicable.

The TOFD software shall not mask any problems such as loss of coupling, missing scan lines, synchronization errors or electronic noise.

In addition, the requirements of ISO 16828 shall apply, taking into account the following:

a) the instrument shall be able to select an appropriate portion of the time base within which A-scans are digitized;

b) it is recommended that a sampling rate of the A-scan of at least 6 times the nominal probe frequency be used.

7.2.2 Ultrasonic probes

Probes used for the TOFD technique on welds shall comply with ISO 22232-2 and ISO 16828.

Adaptation of probes to curved scanning surfaces shall comply with ISO 17640.

A recommendation for the selection of probes is given in Table 2.

7.2.3 Scanning mechanisms

The requirements of ISO 16828 shall apply. To achieve consistency of the images (collected data), guiding mechanisms may be used.

8 Preparation for testing

8.1 Volume to be tested

Testing shall be performed in accordance with ISO 16828. The purpose of the testing shall be defined by specification. Based on this, the volume to be tested shall be determined.

The volume to be tested is located between the probes. For testing levels A and B, the probes shall be placed symmetrically about the weld centreline. For testing levels C and D, additional offset scans may be required.

For manufacturing inspection, the volume to be tested is defined as the zone which includes weld and parent material for at least 10 mm on each side of the weld or the width of the heat-affected zone, whichever is greater. In all cases, the whole volume to be tested shall be covered.

Normally these tests are performed in accordance with recognized standards applying acceptance levels for quality assurance. If fitness-for-purpose methods are applied, then corresponding acceptance criteria shall be specified.

For in-service inspections, the volume to be tested may be targeted to specific areas of interest, e.g. the inner third of the weld body. The acceptance criteria and minimum discontinuity size to be detected in the area of interest shall be specified.

8.2 Setup of probes

The probes shall be set up to ensure adequate coverage and optimum conditions for the initiation and detection of diffracted signals in the area of interest. For butt welds of simple geometry and with narrow weld crowns at the opposite surface, the testing shall be performed in one or more setups (scans) dependent on the wall thickness (see Table 2). For other configurations, e.g. X-shaped welds, different base metal thickness at either side of the weld, or tapering, Table 2 may be used as guidance. In this case, the effectiveness and coverage of the setup shall be verified by using reference blocks. Selection of probes for full coverage of the complete weld thickness should follow Table 2. Care should be taken to choose appropriate combinations of parameters. For example, in the thickness range 15 mm to 35 mm a frequency of 10 MHz, a beam angle of 70° and a transducer size of 3 mm can be appropriate for a thickness of 16 mm, but not for 32 mm thickness.

For testing levels A and B, it is recommended that the TOFD setup be verified by the use of reference blocks.

For testing levels C and D, all the setups chosen for the test object shall be verified by use of reference blocks.

If setup parameters are not in accordance with Table 2, the capability shall be verified by using reference blocks.

For in-service inspection the intersection point of the beam centrelines should be optimized for the specified volume to be tested.

Table 2 — Recommended TOFD setups for simple butt welds dependent on wall thickness

Thickness t mm	Number of TOFD setups	Depth range Δt mm	Centre frequency f MHz	Beam angle (longitudinal waves) α °	Transducer size mm	Beam intersection
6 to 10	1	0 to t	15	70	2 to 3	2/3 of t
>10 to 15	1	0 to t	15 to 10	70	2 to 3	2/3 of t
>15 to 35	1	0 to t	10 to 5	70 to 60	2 to 6	2/3 of t
>35 to 50	1	0 to t	5 to 3	70 to 60	3 to 6	2/3 of t
>50 to 100	2	0 to $t/2$	5 to 3	70 to 60	3 to 6	2/6 of t
		$t/2$ to t	5 to 3	60 to 45	6 to 12	5/6 of t
>100 to 200	3	0 to $t/3$	5 to 3	70 to 60	3 to 6	2/9 of t
		$t/3$ to $2t/3$	5 to 3	60 to 45	6 to 12	5/9 of t
		$2t/3$ to t	5 to 2	60 to 45	6 to 20	8/9 of t
>200 to 300	4	0 to $t/4$	5 to 3	70 to 60	3 to 6	2/12 of t
		$t/4$ to $t/2$	5 to 3	60 to 45	6 to 12	5/12 of t
		$t/2$ to $3t/4$	5 to 2	60 to 45	6 to 20	8/12 of t
		$3t/4$ to t	3 to 1	50 to 40	10 to 20	11/12 of t; or t for $\alpha \leq 45°$

8.3 Scan increment setting

The scan increment setting shall be dependent on the wall thickness to be tested. For thicknesses up to 10 mm, the scan increment shall be no more than 0,5 mm. For thicknesses between 10 mm and 150 mm, the scan increment shall be no more than 1 mm. Above 150 mm, the scan increment shall be no more than 2 mm.

8.4 Geometry considerations

Care should be taken when testing welds of complex geometry, e.g. welds joining materials of unequal thickness, materials that are joined at an angle, or nozzles. As TOFD is based on the measurement of time intervals of sound waves taking the shortest path between the point of emission and the point of reception via points of reflection or diffraction, some areas of interest can be obscured. Additional scans can overcome this problem in many cases.

Planning testing of complex geometries requires in-depth knowledge of sound propagation, representative reference blocks and sophisticated software and is beyond the scope of this document.

8.5 Preparation of scanning surfaces

Scanning surfaces shall be wide enough to permit full coverage of the volume to be tested.

Scanning surfaces shall be even and free from foreign matter likely to interfere with probe coupling (e.g. rust, loose scale, weld spatter, notches, grooves). Waviness of the test surface shall not result in a gap between one of the probes and test surface greater than 0,5 mm. These requirements shall be ensured by dressing, if necessary.

Scanning surfaces may be assumed to be satisfactory if the surface roughness, *Ra*, is not greater than 6,3 µm for machined surfaces, or not greater than 12,5 µm for shotblasted surfaces.