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Non-destructive testing of welds — Ultrasonic testing — Use of automated total focusing technique (TFM) and related technologies

Essais non destructifs des assemblages soudés — Contrôle par ultrasons — Utilisation de la technique d'acquisition automatisée de focalisation en tout point (FTP) et de techniques associées

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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).

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 the IIW, *International Institute of Welding*, Commission V, *NDT and Quality Assurance of Welded Products*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 121, *Welding and allied processes,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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.

Non-destructive testing of welds — Ultrasonic testing — Use of automated total focusing technique (TFM) and related technologies

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document specifies the application of the TFM technique and related technologies for semi- or fully automated ultrasonic testing of fusion- welded joints in metallic materials of minimum thickness 3,2 mm.

NOTE Unless stated otherwise, in this document ‘TFM” and ‘TFM technique” refer to the TFM technique as defined in ISO 23243, and to all related technologies, see for example ISO 23865 and ISO 23243.

This document is applicable to components with welds fabricated using metals which have isotropic (constant properties in all directions) and homogeneous conditions. This includes welds in low carbon alloy steels and common aerospace grade aluminium and titanium alloys, provided they are homogeneous and isotropic.

This document applies to full penetration welded joints of simple geometry in plates, pipes and vessels.

This document specifies four testing levels (A, B, C, D), each corresponding to a different probability of detection of imperfections. Guidance on the selection of testing levels is provided. Coarse-grained metals and austenitic welds can be tested when the provisions of this document have been taken into account.

This document gives provisions on the specific capabilities and limitations of the TFM technique for the detection, locating, sizing and characterization of discontinuities in fusion-welded joints. The TFM technique can be used as a stand-alone approach or in combination with other non-destructive testing (NDT) methods for manufacturing, in-service and post-repair tests.

This document includes assessment of indications for acceptance purposes based on either amplitude (equivalent reflector size) and length or height and length.

This document does not include acceptance levels for discontinuities.

The following two typical testing techniques for welded joints are referred to in this document:

a) side scanning, where the probe(s) is (are) positioned adjacent to the weld cap, typically using wedges. Side scanning can be performed from one side or both sides of the weld;

b) top scanning where the probe is positioned on top of weld cap with a flexible, conformable delay line or using immersion technique, or using contact technique after removing the weld cap.

Semi-automated testing encompasses a controlled movement of one or more probes along a fixture (guidance strip, ruler, etc.), whereby the probe position is measured with a position sensor. The scan is performed manually.

In addition, fully automated testing includes mechanized propulsion.

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 5817, *Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections*

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

ISO 17635, *Non-destructive testing of welds — General rules for metallic materials*

ISO 18563-1, *Non-destructive testing — Characterization and verification of ultrasonic phased array equipment — Part 1: Instruments*

ISO 18563-2, *Non-destructive testing — Characterization and verification of ultrasonic phased array equipment — Part 2: Probes*

ISO 23865:2021, *Non-destructive testing — Ultrasonic testing — General use of full matrix capture/ total focusing method technique*

ISO 23243, *Non-destructive testing — Ultrasonic testing with arrays - Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5577, ISO 17635, ISO 23865 and ISO 23243 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/

4 Testing levels

Quality requirements for welded joints are mainly associated with the material, the welding process and the service conditions. To accommodate all these requirements, this document specifies four testing levels (A, B, C, and D).

From testing level A to testing level C, an increasing probability of detection is achieved by an increasing testing coverage, i.e. covering the test volume in multiple ways, e.g. number of imaging paths, number of array positions.

Testing level D may be agreed for special applications using a written procedure which shall take into account the general requirements of this document. This includes tests of metals other than ferritic steel, tests on partial penetration welds, tests at object temperatures outside the range of 7.7. For level D, a verification on test blocks is mandatory.

Testing levels related to quality levels shall be in accordance with ISO 5817 or technically equivalent standards. The appropriate testing level can be specified by standards for testing of welds (e.g. ISO 17635), by product standards or by other documents. When ISO 17635 is specified, the recommended testing levels are as given in Table 1.

Table 1 — Recommended testing levels

Testing level	Quality level in accordance with ISO 5817
A	C, D
B	B
C	by agreement
D	special application

Table 2 shows the minimum requirements. As described in 7.3, the setup shall be verified with reference blocks and/or test blocks in all cases.

Top scanning can be performed with TFM if the weld cap has been removed and the test surface is flat, otherwise adaptive focusing is required to take the geometry of the weld cap into account.

Side scanning with two probes simultaneously at both sides of the weld allows for imaging paths from one probe to the other probe (see ISO 23865).

Table 2 — Details of testing levels, minimum requirements

Testing technique	Testing levels			
	A[a]	B[a]	C[b]	D[b]
Top scanning at fixed probe position to the weld (line scan)	Direct imaging path	Direct imaging path and imaging path using reflection at the opposite surface	Direct imaging path and imaging path(s) which ensure(s) reflected signals from planar discontinuities on the weld bevel	Suitable imaging paths and positions (sides) by agreement
Side scanning at fixed probe position to the weld (line scan)	Direct imaging path, two sides	Direct imaging path and imaging path using reflection at the opposite surface, two sides or two probe positions	Direct imaging path and (multiple) imaging path(s) using reflection at the opposite surface, two sides or two probe positions	Suitable imaging paths and positions (sides) by agreement
Side scanning with raster scanning	Direct imaging path, one side	Direct imaging path and imaging path using reflection at the opposite surface, one side	Direct imaging path and (multiple) imaging path(s) using reflection at the opposite surface, one side, images from different probe positions to the weld are merged	Suitable imaging paths and positions (sides) by agreement

[a] For testing levels A and B: imaging using reflection at the opposite surface can be done by extending the ROI (only for TT-TT or LL-LL) or by using corresponding imaging paths.

[b] For testing levels C and D: The choice of the imaging paths shall depend on weld bevel design and be motivated in the scan plan based on Table 3.

5 Information required before testing

5.1 Items to be defined before procedure development

Information on the following items is required:

a) purpose and extent of testing;

b) type(s) of parent material (i.e. cast, forged, rolled); grain size and anisotropy;

NOTE 1 Several properties of the parent material, in particular deviations in grain elongation due to rolling, have influence on the images generated by TFM. This influence also exists in other ultrasonic testing techniques but is experienced differently. ISO 23865:2021, Clause 15, gives guidance.

NOTE 2 Variation in wall thickness has an influence on the image generated, in particular when using imaging paths containing one or more reflections. ISO 23865:2021, Clause 15, gives guidance.

c) testing level;

d) acceptance criteria, including method for evaluation of indications and method for establishing reference level;

e) specification of calibration blocks, reference blocks, test blocks used;

f) stage (e.g. manufacturing or in-service) at which the testing is to be carried out;

g) object and weld geometry details and information on the size of the heat-affected zone. If the size of the heat affected zone is not known, practical values according to the welding process used may be considered;

h) requirements for access, surface conditions and temperature. Material temperature has a significant influence on the images generated by TFM. Where the test object has a temperature outside the range specified in 7.7, ISO 23865:2021, Clause 15, gives guidance;

i) personnel qualifications;

j) reporting requirements.

5.2 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 5.1, together with the following additional information:

a) the written test procedure (see 5.3);

b) joint preparation and dimensions;

c) relevant information on the welding process;

d) time of testing relative to any post-weld heat treatment.

5.3 Written test procedure

For all testing using the TFM technique, a written test procedure is required. The procedure shall include the following information as a minimum:

a) the purpose and extent of testing, including details of the region of interest (ROI) and grid;

b) the testing technique, including acquisition scheme and imaging algorithm (processing parameters);

c) the testing level;

d) the personnel qualification/training requirements;

e) the equipment to be used (including but not limited to frequency, sampling rate, pitch, element size, wedge dimensions and velocity);

f) the reference and/or test blocks;

g) examples of calibration and reference scans;

h) the sensitivity settings;

i) required access and surface conditions;

j) requirements for testing of parent material;

k) evaluation of indications, including sizing methodology;

l) acceptance level and/or recording level;

m) reporting requirements;

n) any environmental and safety issues;

o) scan plan showing the following, to provide a standardized and repeatable methodology for testing:

— object and weld geometry;

— probe positioning and movement, relative to the weld;

— the imaging path(s) used, and how these correspond to the location and orientation of expected discontinuities;

— the coverage of the test object and the ROI.

6 Requirements for personnel and equipment

6.1 Personnel qualifications

Personnel performing testing in accordance with this document shall be qualified to an appropriate level in accordance with ISO 9712 or equivalent in the relevant product sector or industrial sector.

In addition to general knowledge of ultrasonic weld testing, the operators shall be familiar with, and have practical experience in, the use of the TFM technique or related technology. Specific training and examination of personnel should be performed on representative test pieces. These training and examination results should be documented. If this is not the case, specific training and examination should be performed with the finalized ultrasonic test procedures and selected ultrasonic test equipment on representative samples containing natural or artificial reflectors similar to those expected. These training and examination results should be documented.

6.2 Test equipment

6.2.1 General

In selecting the system components (hardware and software), ISO/TS 16829 gives useful information.

6.2.2 Instrument

The ultrasonic instrument used for the TFM testing shall be in accordance with ISO 18563-1, if applicable.

The instrument shall be able to acquire a full or partial matrix and either process it by itself or transmit it to a computer for post-processing. It is recommended that a sampling rate of the A-scan be used of at least five times the nominal probe frequency. It is recommended that the bandwidth of the ultrasonic instrument is sufficient to receive signals of at least two times the centre frequency of the probe, and that high- and low-pass filters are set to appropriate values, e.g. high-pass set not higher than half the centre frequency and low-pass set to at least twice the centre frequency. The specific values selected for these parameters, if applicable, shall be explicitly specified within the written procedure.

The minimum spatial resolution of data points within the image (i.e. grid spacing, nodes) should be chosen such that the amplitude of a reference reflector is stable within a specified tolerance on small deviations (one wavelength) in the probe position. ISO 23865 contains suggested values for the spatial resolution of data points, and suggestions for the validation of the amplitude stability.

6.2.3 Probes

Ultrasonic arrays used for the TFM testing shall be in accordance with ISO 18563-2.

In order to achieve good quality images, the following properties of the array probe should be taken into consideration:

a) adequately small pitch to avoid spatial aliasing;

b) highly damped elements to decrease the length of the ultrasonic wave train;

c) sufficiently small elements to avoid too much directivity;

d) appropriate dimensions (both along the primary axis and the secondary axis of the array) to allow for imaging at a distance away from the probe, as the TFM algorithm has optimal results in the near field of the probe;

e) wedge dimension optimized for effectiveness.

6.2.4 Scanning mechanisms

To achieve consistency of the images (collected data), guiding mechanisms and scan encoder(s) shall be used.

Unlike other ultrasonic techniques, maintaining a constant distance from the weld is not as important, if the resulting image consistently contains the complete area to be tested. However, for a correct evaluation, the position of the weld in the image is required, e.g. by using geometrical indications.

7 Preparation for testing

7.1 Volume to be tested

The purpose of the testing shall be defined by specification. Based on this, the testing volume shall be determined. The region of interest (ROI), or combination of ROIs, shall cover the testing volume.

For testing thicknesses <8 mm at the manufacturing stage, the testing volume shall include the weld and parent material for at least 1,25 times the thickness, *t*, of the test object on each side of the weld preparation (1 *t* for laser welds and for electron beam welds), or the proven width of the heat affected zone (based on the manufacturer's information).

For testing thicknesses ≥8 mm at the manufacturing stage, the testing volume shall include the weld and parent material for at least 10 mm on each side of the weld preparation (5 mm for laser welds and for electron beam welds), or the proven width of the heat affected zone (based on the manufacturer's information), whichever is greater.

A scan plan shall be provided in the written procedure to document the coverage, see 5.3.

7.2 Imaging typical weld discontinuities

7.2.1 Discontinuity orientation

Compared to PAUT, TFM is typically less sensitive to discontinuity orientation. However, when planar discontinuities are expected, imaging paths shall be employed that anticipate on the way ultrasound is reflected from these discontinuities. If amplitude-based sizing is to be used, then perpendicular incidence/specular reflection is required. Detection and sizing may also be performed using diffraction signals, which rely on a pre-defined imaging path to a much lesser extent, but it should be realized that the resulting images have a lower signal-to-noise ratio and are harder to interpret.

In general, discontinuities perpendicular to the scanning surface, such as lack of fusion on a weld bevel with a low angle, require an imaging path where either the transmitted or the received path contains a reflection from the opposite surface (e.g. TT-T).

In general, discontinuities parallel to the scanning surface require an imaging path where sound reflected by the discontinuity can travel to an array element. This can be achieved by using an array directly above the discontinuity (top scanning) or by simultaneously using two arrays on both sides of the weld.

7.2.2 Discontinuity location

Compared to PAUT, the performance of TFM is typically less sensitive to the location of the discontinuity inside the weld. However, it should be taken into consideration that TFM has limitations concerning the angle, against the normal to the probe, over which discontinuities are detected.

With side scanning, discontinuities in the lower part of the weld are generally best detected with an imaging path where at least one of the transmitting or receiving paths is a direct path from the probe to the discontinuity.

With side scanning, discontinuities in the upper part of the weld are generally best detected with an imaging path containing at least one reflection at the opposite surface. This can be achieved by imaging as a direct imaging path by extending the ROI (only for testing levels A and B, only for TT-TT or LL-LL) or by imaging via an imaging path that takes into account reflection(s) on the back wall (e.g. TT-T/T-TT or TT-TT, all testing levels).

7.2.3 Suitable imaging paths for specific discontinuity types

For suitable imaging paths related to typical discontinuity types, see Table 3 which shows testing from the surface at the weld cap side.

Selected imaging path(s) may not work over the entire aperture of the array. Determination of the workable aperture should be considered in the scan plan taking into account increased diffusion and scattering of ultrasound in the weld metal.

Amplitude-based sizing requires imaging paths based on specular reflection on the discontinuities.

Table 3 — Recommended imaging paths for typical weld discontinuities

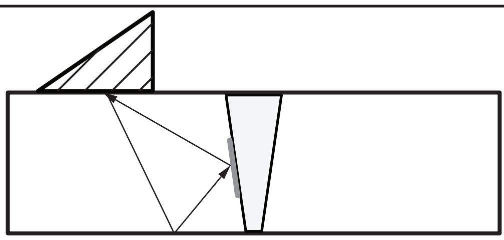
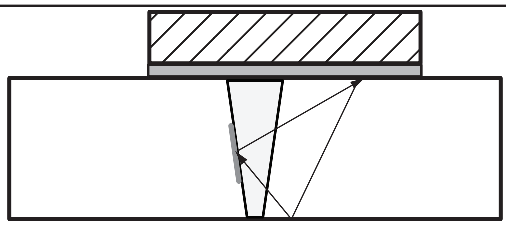
Weld discontinuity	Side scanning	Top scanning
Lack of fusion, low-angle weld bevel	 LL-L/L-LL or TT-T/T-TT or LL-T imaging path as this discontinuity is nearly vertical. Discontinuity height sizing is best performed based on diffraction signals received with a direct imaging path.	 LL-L/L-LL imaging path as this discontinuity is nearly vertical. Direct imaging path with a sufficiently large aperture.

Table 3 *(continued)*

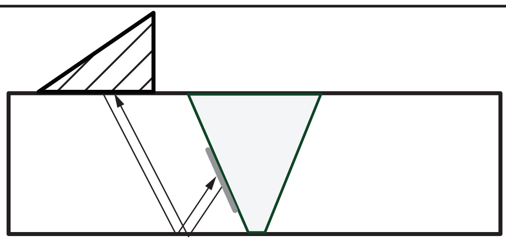
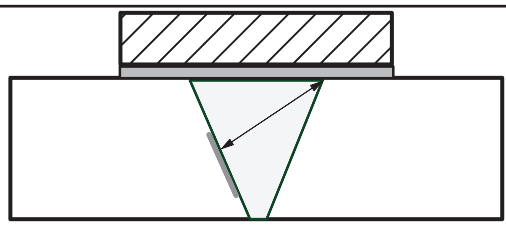
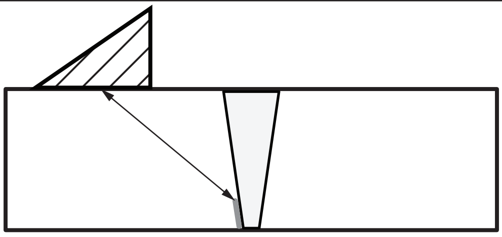
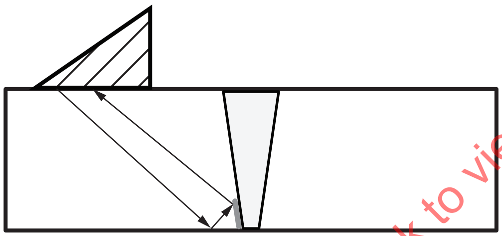
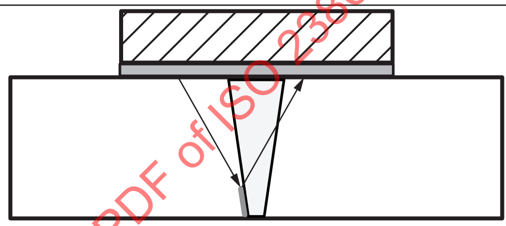
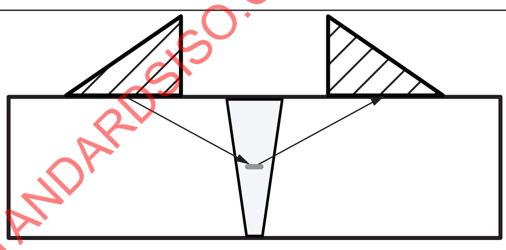
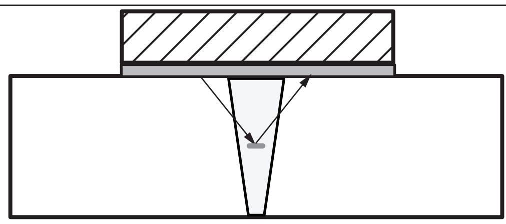
Weld discontinuity	Side scanning	Top scanning
Lack of fusion, high-angle weld bevel	 LL-LL or TT-TT imaging path. In some cases, direct imaging path through the weld can be used. Probe positioning needs to be considered in the scan plan to allow for specular reflection.	 Direct imaging path. Probe positioning needs to be considered in the scan plan to allow for specular reflection.
Lack of root fusion/ incomplete penetration	  Direct imaging path for tip (top) and/or reflection at the side of the discontinuity (e.g. TT-T/T-TT). For root concavity, also use reception at the probe on the other side of the weld.	 Direct imaging path for tip (top) only. The aperture needs to be sufficiently large to receive signals.
Lack of inter-run fusion	 Direct imaging path by simultaneously using probes on both sides of the weld.	 Direct imaging path.

Table 3 *(continued)*

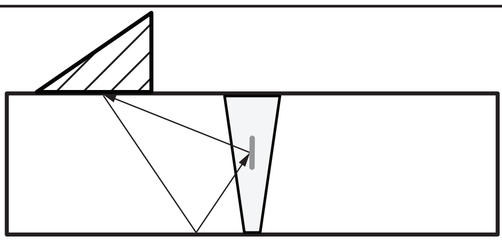
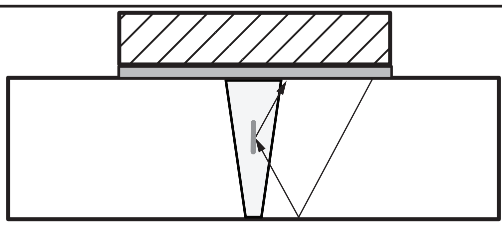
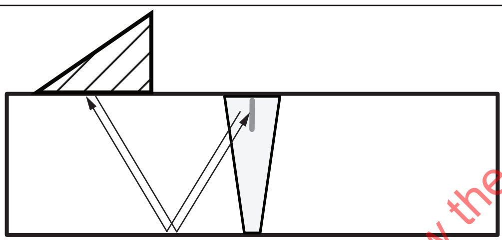
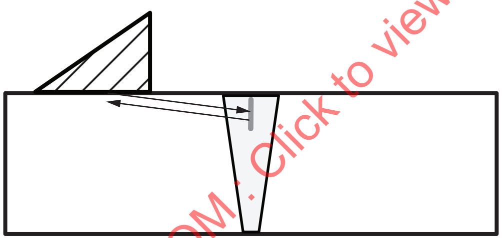
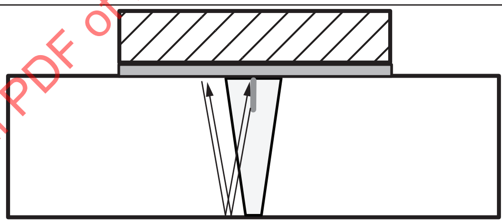
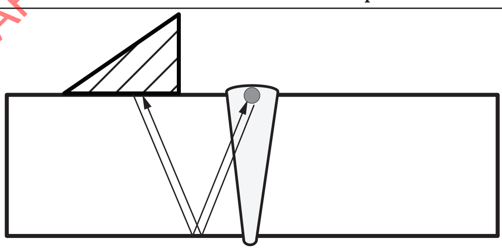
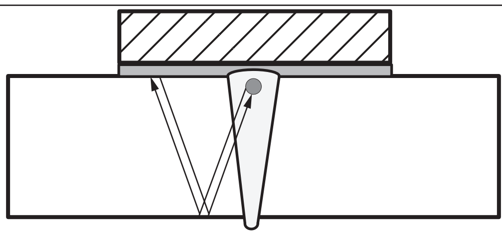
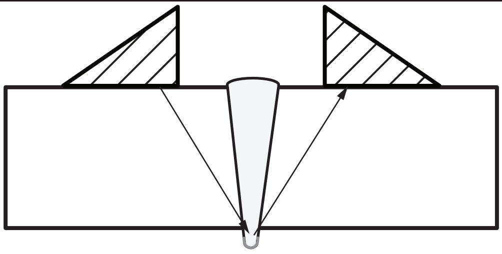
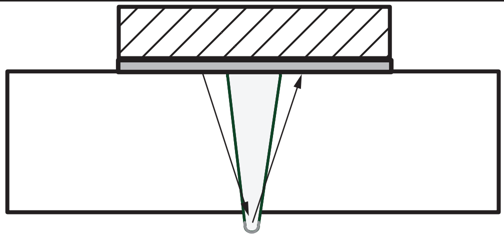
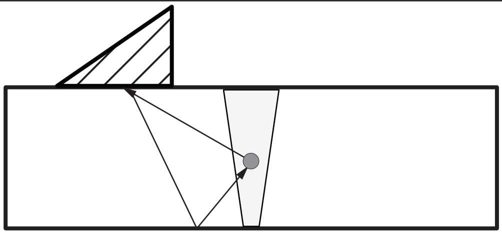
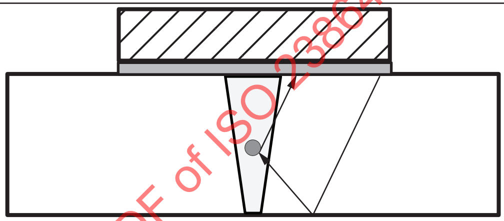
Weld discontinuity	Side scanning	Top scanning
Embedded cracks parallel to the weld axis	 LL-L/L-LL or TT-T/T-TT or LL-T imaging path as this discontinuity is nearly vertical. Discontinuity height sizing is best performed based on diffraction signals received with direct imaging path (with probes on both sides of the weld used simultaneously).	 LL-L/L-LL imaging path as this discontinuity is nearly vertical. Discontinuity height sizing is best performed based on diffraction signals received with direct imaging path (with elements on both sides of the weld used simultaneously). Direct imaging path with a sufficiently large aperture.
Scanning surface breaking cracks and undercut	  LL-LL or TT-TT imaging path and/or direct imaging of creeping waves (also known as high angle compression mode). Wedge design enabling creeping waves should be considered in the written test procedure.	 LL-LL imaging path.
Cap porosity	 LL-LL or TT-TT imaging path. ROI shall include the cap area above the scanning surface.	 LL-LL imaging path. ROI shall include the cap area above the scanning surface.

Table 3 *(continued)*

Weld discontinuity	Side scanning	Top scanning
Excessive penetration	 Direct imaging path. If excessive penetration is to be detected, ROI shall include the area under the opposite surface.	 Direct imaging path. If excessive penetration is to be detected, ROI shall include the area under the opposite surface.
Inclusions	 Use both direct imaging path and L-LL/LL-L or T-TT/TT-T. Inclusions have a low signal-to-noise ratio.	 Use both direct imaging path and L-LL/LL-L. Inclusions have a low signal-to-noise ratio.

7.3 Verification of test setup

The capability of the test setup shall be verified by using reference blocks and test blocks containing real discontinuities and/or artificial reflectors, where applicable.

7.4 Scan increment setting

For thicknesses:

— under or equal to 6 mm, the scan increment shall be no more than 0,5 mm;

— between 6 mm and 10 mm, the scan increment shall be no more than 1 mm;

— between 10 mm and 150 mm, the scan increment shall be no more than 2 mm;

— above 150 mm, a scan increment of 3 mm is recommended.

The scan increment setting perpendicular (also termed index direction) to the welding direction when applicable (e.g. for raster scanning) shall be chosen in order to ensure the coverage of the testing volume.

7.5 Geometry considerations

Care shall be taken when testing welds of complex geometry, e.g. a weld joining materials of unequal thickness, materials that are joined at an angle or nozzles. They shall always be carried out under testing level D. TFM algorithms can be applied on these geometries and can have capabilities over PAUT. For example, some implementations of TFM are able to image the geometry of the test object and adjust for changes in geometry such as adjusting for the geometric variation around the circumference of a nozzle or an adaptive algorithm for adjusting to changes in local wall thickness. For top scanning, an adaptive algorithm can be used to take the geometry of the weld cap into account. Such adaptive algorithms shall be specified in the written procedure and the resultant setup shall be demonstrated on suitable test blocks prior to testing.

7.6 Preparation of scanning surfaces

Scanning surfaces shall be clean, in an area wide enough to permit the testing volume to be fully covered. 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). The condition of the test surface shall result in a gap not exceeding 0,5 mm between the probe and the surface. These requirements shall be ensured by dressing the scanning surface as necessary.

Scanning surfaces may be assumed to be satisfactory if the surface roughness, R_a, is not greater than 6,3 µm for machined surfaces, or not greater than 12,5 µm for shot-blasted surfaces.

When coating such as paint is present and cannot be removed, reference or test blocks with identical coating are required. In addition, the required corrective actions shall be determined and applied.

When using an adaptable probe shoe or (local) immersion technique, the surface condition shall be sufficiently smooth to ensure proper imaging results. Requirements on the weld cap shall be clearly documented in the written procedure. Imaging results shall be demonstrated on suitable samples containing a weld.

7.7 Temperature

The surface temperature of the test object should be in the range of 0 °C to 50 °C. For temperatures outside this range, the suitability of the test equipment shall be verified. Special high temperature array probes and appropriate couplant can be required.

7.8 Couplant

In order to generate proper images, a couplant shall be used which provides a constant transmission of ultrasound between the probe(s) and the test object. The couplant used for calibration shall be the same as that used in subsequent testing and post-calibrations.

When using a conformable shoe or (local) immersion technique, requirements on the couplant, determination of sound velocity including temperature dependency, and verification of coupling shall be clearly documented in the written procedure.

8 Testing of parent material

The parent metal in the test area shall be tested, to demonstrate that the testing of the weld is not influenced by the presence of imperfections, in particular laminations.

Where imperfections are found, their influence on the required weld testing shall be assessed and, if necessary, the imaging paths or techniques adapted correspondingly. When satisfactory coverage by ultrasonic testing is seriously affected, other test methods (e.g. radiography) shall be considered.

9 Range and sensitivity

9.1 General

The range and sensitivity shall be set for each imaging path in each ROI prior to each test in accordance with this document. Any change of the setup, e.g. probe position, ROI or imaging path(s) used requires verification of the settings.

The signal-to-noise ratio in the image should be a minimum of 12 dB for the reference signals based on reflection. The method or tool for the measurement of the signal-to-noise ratio shall be specified in the written procedure.

9.2 Range and sensitivity settings

9.2.1 General

After selection of the testing technique and imaging path(s):

a) the sensitivity shall be set for each imaging path in each ROI;

b) when a probe with wedge is used, the sensitivity shall be set with the wedge in place;

c) when a probe with flexible, conformable wedge is used or immersion technique is used, the sensitivity shall be set with the wedge or immersion delay path in place.

9.2.2 Setting range and sensitivity on the test object itself

Due to TFM being able to image the geometry of the object, it is possible to set range and sensitivity on the test object. This has the advantage of not needing a calibration or reference block. The written procedure shall specify on which geometric features (for example back wall, side wall) the range and the sensitivity are set, and how sensitivity is adjusted to obtain the sensitivity required during the testing.

To ensure alignment of this document with other standards, using this option is only allowed for testing level A.

9.2.3 Gain corrections

The procedure described in ISO 23865:2021, 10.3, can be used to perform testing with gain correction, which is similar to time-corrected gain (TCG) in other ultrasonic techniques. Gain correction enables the display of signals from the same reflector with the same amplitude independent from distance.

9.3 Checking of the settings

Settings shall be checked at least every 4 hours and after completion of the testing. If the single test takes more than 4 h, the settings shall be checked after completion of the test.

If a reference block was used for initial setting, the same reference block shall be used for checking at the intermediate points in time and end of the testing period. Alternatively, a smaller block with known transfer properties may be used.

If deviations from the initial settings, in accordance with 9.1, are found during these checks, corrections in accordance with Table 4 shall be carried out

Table 4 — Sensitivity and range corrections

Sensitivity	
Deviations ≤4 dB[a, b]	No action required; data may be corrected by software.
Deviations >4 dB[a, b]	The complete chain of measurement shall be checked. If no defective components are identified, settings shall be corrected and all tests carried out since the last valid check shall be repeated.
Range	
Deviations ≤0,5 mm or 2 % of depth-range, whichever is greater	No action required.
Deviations >0,5 mm or 2 % of depth-range, whichever is greater	Settings shall be corrected and all tests carried out since the last valid check shall be repeated.

[a] The required signal-to-noise ratio shall be achieved.

[b] The 4 dB deviation applies for reflection signals. For diffraction signals, a 6 dB deviation is allowed.

10 Reference blocks and test blocks

10.1 General

Depending on the testing level, reference blocks shall be used to determine the adequacy of the testing (e.g. coverage, sensitivity setting). Recommendations for reference blocks are shown in Annex A.

10.2 Material

The reference block shall be made of similar material to the test object, e.g. with regard to sound velocity, grain structure, and surface condition.

10.3 Dimensions and shape

The thickness of the reference blocks is recommended to be between 0,8 and 1,5 times the thickness of the test object with a maximum difference in thickness of 20 mm compared to the test object. The length and width of the reference block should be chosen such that all the artificial discontinuities can be properly scanned. For testing of longitudinal welds in cylindrical test objects, curved reference blocks shall be used having diameters from 0,9 to 1,5 times the test object diameter. For test objects having a diameter ≥300 mm, a flat reference block may be used.

In all cases, with regard to the diameter or curvature, the requirement mentioned in 7.6 is mandatory. The maximum allowed gap between probe shoe and reference block is 0,5 mm.

10.4 Reference reflectors

For a thickness between 3,2 mm and 25 mm, at least three reflectors are required. For a thickness t > 25 mm, at least five reflectors are required. Typical reference reflectors are side-drilled holes, notches and flat-bottomed holes.

Details of the reference block according to the testing levels are given in Table 5 and Annex A. Alternatively, blocks in accordance with ISO 10863:2020, Annex A, can be used, with notches.

Table 5 — Testing levels and reference blocks

Testing level	Reference block
A	See Figure A.1 or Figure A.4
B	See Figure A.2 or Figure A.4
C	See Figure A.3 or Figure A.4
D	As specified

Notches can be used for generating reflection or diffraction signals, depending on the imaging path and the shape of the notch tip.

11 Equipment checks

It shall be checked that all relevant channels, probes and cables of the ultrasonic test system are functional. These checks shall be performed daily before and after testing. If any item of the system fails, corrective action shall be taken and the system shall be retested. If a system is shown to have failed during a testing period, then all tests during that period shall be repeated once corrective action has been taken.

12 Procedure verification

Procedure verification is required for testing level D. The test procedure shall have been demonstrated to perform acceptably on reference block(s). A satisfactory procedure qualification shall take place prior to the first testing.

A satisfactory procedure qualification includes:

a) detection of all required reflectors with the minimum signal to noise ratio, as specified either in 9.1 or by agreement in case of level D;

b) sizing capability as required by specification;

c) proof of coverage in depth and width.

13 Weld testing

Before initial testing, the coverage shall be verified with the scan plan and demonstrated on a suitable reference block.

Acceptable deviations of probe position relative to the weld centreline shall be documented in the test procedure and shall be covered in the scan plan and shown on a reference block.

Some indications detected during the initial scanning can require additional evaluation, scans with additional imaging paths, scans perpendicular to the discontinuity. This may be undertaken using additional post-processing of the data if the data is stored during the initial scanning.

The scanning speed shall be chosen such that the required data is collected for each scan position, e.g. the full matrix or the specified subset. Missing scan lines indicate that too high a scanning speed has been used. A maximum of 5 % of the total number of lines collected in one single scan may be missed, but no adjacent lines shall be missed.

If the length of a weld is scanned in more than one section, an overlap of at least 20 mm between the adjacent scans is required. When scanning circumferential welds, the same overlap is required for the end of the last scan with the start of the first scan.

If applicable, a control function for the coupling efficiency is recommended.

14 Data storage

Compared to PAUT, FMC and related techniques typically collects a larger volume of A-scan data, corresponding to the collection of all possible combinations of transmitters and receivers in (an) array probe(s), the full matrix. Images are computed from the matrix of A-scans either on the acquisition hardware or on a computer connected to the acquisition hardware. In either case, the amount of A-scan data can be too big to retain. The original constructed images as well as the original imaging parameters shall be stored.

15 Interpretation and analysis of TFM images

15.1 General

Interpretation and analysis of TFM images are typically performed as follows:

a) assessment of the quality of the TFM images;

b) identification of relevant indications;

c) classification of relevant indications as specified;

d) determination of amplitude or height of an indication, location and size as specified;

e) evaluation against the specified acceptance criteria.

15.2 Assessing the quality of TFM images

TFM testing shall be carried out such that satisfactory images are generated which can be evaluated with confidence. Satisfactory images are defined by appropriate:

a) coupling;

b) ROI settings;

c) sensitivity setting;

d) signal-to-noise ratio;

e) absence of saturation;

f) data acquisition.

Assessing the quality of TFM images requires skilled and experienced operators (see 6.1). The operator shall decide whether non-satisfactory images require new data acquisition (re-scanning).

15.3 Identification of relevant indications

The TFM technique images both discontinuities in the weld and geometric features of the test object. In order to identify indications of geometric features, detailed knowledge of the test object is necessary.

To decide whether an indication is relevant (caused by a discontinuity), patterns or disturbances shall be evaluated considering shape and signal amplitude relative to the general noise level.

15.4 Classification of relevant indications

Amplitude, location and pattern of relevant indications may contain information on the type of the discontinuity.

Relevant indications shall be classified as specified.

15.5 Determination of location and length of an indication

15.5.1 Location

The location of an indication parallel to the weld axis, perpendicular to the weld axis and in the through-wall direction shall be determined from the collected data.

15.5.2 Length

The method of determining the length shall be in accordance with the acceptance level applied, e.g. using a threshold or an amplitude drop.

15.6 Determination of amplitude or height of an indication

15.6.1 General

This assessment can be based on amplitude, on equivalent reflector size or on height according to specification.

15.6.2 Based on amplitude

The maximum amplitude of each indication shall be evaluated in accordance with the specified acceptance level, by determining the equivalent reflector size or by using a specified amplitude drop.

15.6.3 Based on height

The height of an indication is the extent in the through-wall direction, typically obtained from the geometry of the indication in the image. For indications displaying varying height along their length, the height shall be determined at the scan position of maximum extent.

It is encouraged to use diffraction signals for identifying indication tips. If diffracted signals are used, the height is determined using:

— two diffracted signals observed from the same discontinuity (upper and lower tip);

— one diffracted signal and a surface signal observed from the same discontinuity;

— one diffracted signal and the known wall thickness for root connected discontinuities; or

— one diffracted signal in relation to the surface for a surface breaking discontinuity.

In case a height cannot be measured using diffracted signals, then the determination can be based on:

— amplitudes using a reference levels, e.g. as described in ISO 11666;

— other sizing techniques, e.g. TCG, DGS, 6 dB drop;

— the location of reflections (e.g. hollow root, mismatch).

If a more accurate height determination is required, additional processing algorithms may be used.

15.7 Evaluation against acceptance criteria

After classification of all relevant indications, determination of their location and length, and amplitude, equivalent reflector size or height, the indications shall be evaluated against specified acceptance criteria.

The indications can then be classified as “acceptable” or “not acceptable”.

As TFM typically has similar or better performance than phased array testing, acceptance criteria for phased array testing (e.g. ISO 19285) may be used as indicated in Table 6.

Table 6 — Quality levels, testing levels and acceptance levels for TFM testing

Quality level in accordance with ISO 5817	Testing level in accordance with this document	Acceptance level in accordance with ISO 19285
C, D	A	3
B	B	2
By agreement	C	1
Special application	D	By agreement

16 Test report

The test report shall include at least the following information:

a) a reference to this document (i.e. ISO 23864:2021);

b) information on the test object:

   1) identification of the test object;

   2) dimensions including wall thickness;

   3) material type and product form;

   4) geometrical configuration;

   5) location of tested welded joint(s);

   6) reference to weld geometry, welding process and heat treatment;

   7) surface condition and temperature;

   8) stage of manufacture;

c) information relating to equipment:

   1) manufacturer and type of FMC instrument/TFM instrument including scanning mechanisms with identification numbers if required;

   2) manufacturer, type, frequency of array probes including number and size of elements, material and angle(s) of wedges with identification numbers if required;

   3) details of reference block(s) with identification numbers if required;

   4) type of couplant used;

d) information relating to test technology:

   1) testing level and reference to a written test procedure;

   2) purpose and extent of test;

   3) details of datum and coordinate systems;

   4) method and values used for range and sensitivity settings, calibration, TCG and gain compensation;

   5) scan increment setting;

   6) scan plan;

   7) access limitations and deviations from this document, if any;

   8) parameters, signal processing (e.g. filters, envelope), algorithms and technology used

e) information relating to ROI and imaging paths:

   1) dimensions and increments of ROI horizontally and vertically;

   2) results of checking resolution, coverage and grid resolution in accordance with ISO 23865:2021, Annex C;

   3) imaging paths;

   4) imaging paths used in interpretation and analysis;

f) information relating to test results:

   1) reference to the TFM original image data file(s);

2) TFM images of at least those locations where relevant not-acceptable indications have been detected, all images or data available in soft format;

3) acceptance criteria applied;

4) tabulated data recording the classification, location and size of relevant indications and results of evaluation;

5) reference points and details of the coordinate system;

6) date of test;

7) names, signatures and certification of personnel.

17 Austenitic welds

TFM and related techniques may be used on austenitic welds provided they are in line with this document under the following conditions:

a) testing level D is used;

b) the combination of probe(s), wedge design, delay law computation (if used) and imaging algorithm, is able to produce or process ultrasonic wave types and directions allowing the implementation of techniques defined in ISO 22825:2017, Annex A;

c) the settings, time base and sensitivity calibration, the reference and test blocks follow the requirements of ISO 22825 and the steps necessary when producing a written procedure are followed. Modelling may be used to support these steps.

The general testing principles are as below, see ISO 22825:2017, 9.3, for more details:

a) when the grain size is relatively fine and the signal-to-noise ratio is at least 12 dB, the testing can be realized following the rules for low-alloy steel components;

b) when the grain size is coarse, it can imply that only imaging paths based on longitudinal waves through the welds are suitable for testing;

c) in the case of insufficient signal-to-noise ratio (<6 dB), other NDT methods shall be considered;

d) the anisotropy (direction dependency) of the material may cause discontinuities to be displayed at an incorrect position or out of focus. The differences of the indication in the image (in location and size) from the real reflector should be determined.

Table 3 may be used to select the proposed imaging paths according the discontinuity type. For austenitic and/or coarse-grained materials, an imaging path with wave mode conversion (e.g. TL-L) may also be recommended.

For some austenitic materials, it can be possible to select imaging paths using shear waves depending on the ultrasonic properties of the parent material and the weld metal. For most austenitic materials, it is necessary to use imaging paths based on longitudinal waves, particularly when the ultrasonic waves pass weld material.

Annex A
(informative)

Typical reference blocks and reference reflectors

A.1 Reference reflectors

The recommended minimum requirements are given in this annex.

For a thickness between 3,2 mm and 25 mm, at least three reference reflectors are recommended. The reflectors may be machined in one or more blocks.

For a thickness >25 mm, at least five reference reflectors are recommended. The reflectors may be machined in one or more blocks.

The tolerances for all the dimensions of the reference reflectors are as follows:

— diameter: ±0,2 mm;

— length: ±2 mm;

— angle: ±2°.

Tables A.1, A.2, and A.3 describe the reference reflectors for different wall thicknesses over 6 mm. Table A.4 describes the reference reflectors for wall thicknesses 3,2 mm to 8 mm. In the range of 6 mm to 8 mm the reference reflectors can be selected from each Table.

Alternatively, blocks in accordance with ISO 10863:2020, Annex A, can be used, with notches to generate diffraction signals.

Table A.1 — Length and depth of notches in the reference block

Dimensions in millimetres

Thickness t	Length l	Height h	Width B
$6 < t \leq 40$	t	1 ± 0,2	0,2 ± 0,05
$40 < t \leq 60$	40 ± 2	2 ± 0,2	0,2 ± 0,05
$60 < t \leq 100$	50 ± 2	2 ± 0,2	0,2 ± 0,05
$t > 100$	60 ± 2	3 ± 0,2	0,2 ± 0,05

Table A.2 — Diameter D_d of side-drilled holes

Dimensions in millimetres

Thickness t	Diameter D_d
$6 < t \leq 25$	2,5 ± 0,2
$25 < t \leq 50$	3,0 ± 0,2
$50 < t \leq 100$	4,5 ± 0,2
$t > 100$	6,0 ± 0,2

If near-side surface holes are required, they shall have a diameter of 2 mm (see Figure A.2).

Table A.3 — Length of side-drilled holes and surface notches for thickness t > 25 mm

Dimensions in millimetres

Depth	Minimum length			
	Three holes in the same block	Three separate blocks, one hole per block	Three notches in the same block	Three separate blocks, one notch per block
(1/4) t	l_0 = 45	45	40	40
(1/2) t	l_0 + 15	45	40	40
(3/4) t	l_0 + 30	45	40	40

Table A.4 — Typical reference reflectors for circumferential welds 3,2 – 8 mm

Dimensions in millimetres

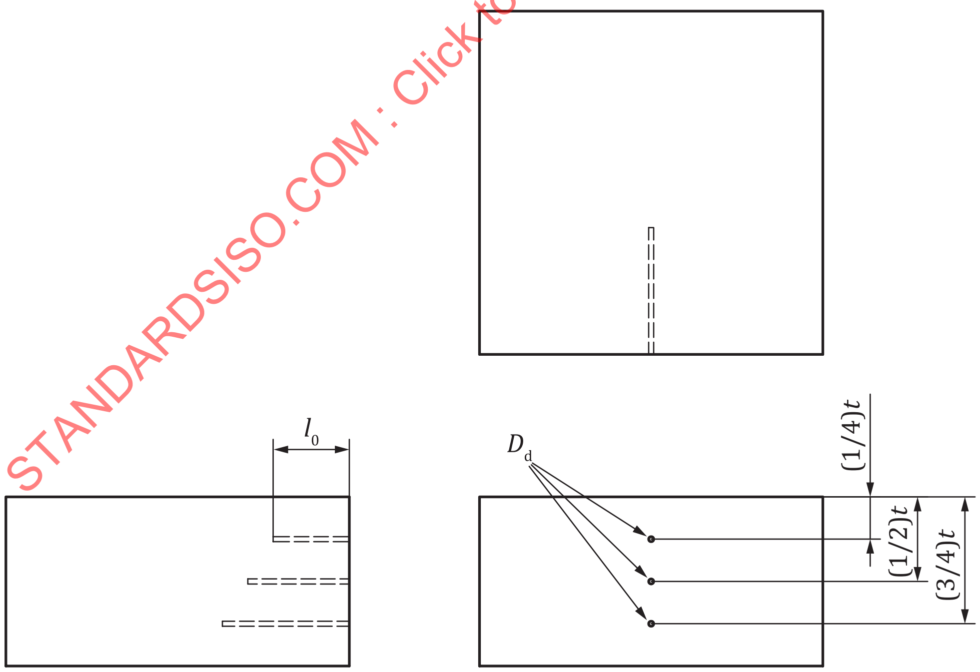
Type of reflector	Size	Length	Tolerances of size and length	Object thickness t
External notch	h = 0,75	10	±10 %	3,2 ≤ t < 8
Internal notch	h = 0,75	10	±10 %	3,2 ≤ t < 8
Side-drilled hole	D_d = 1,0	>15	±10 %	3,2 ≤ t < 8

A.2 Typical reference blocks

A.2.1 Testing level A

See Figure A.1.

Dimensions in millimetres



Key

D_d diameter of side-drilled hole

l_0 length of side-drilled hole

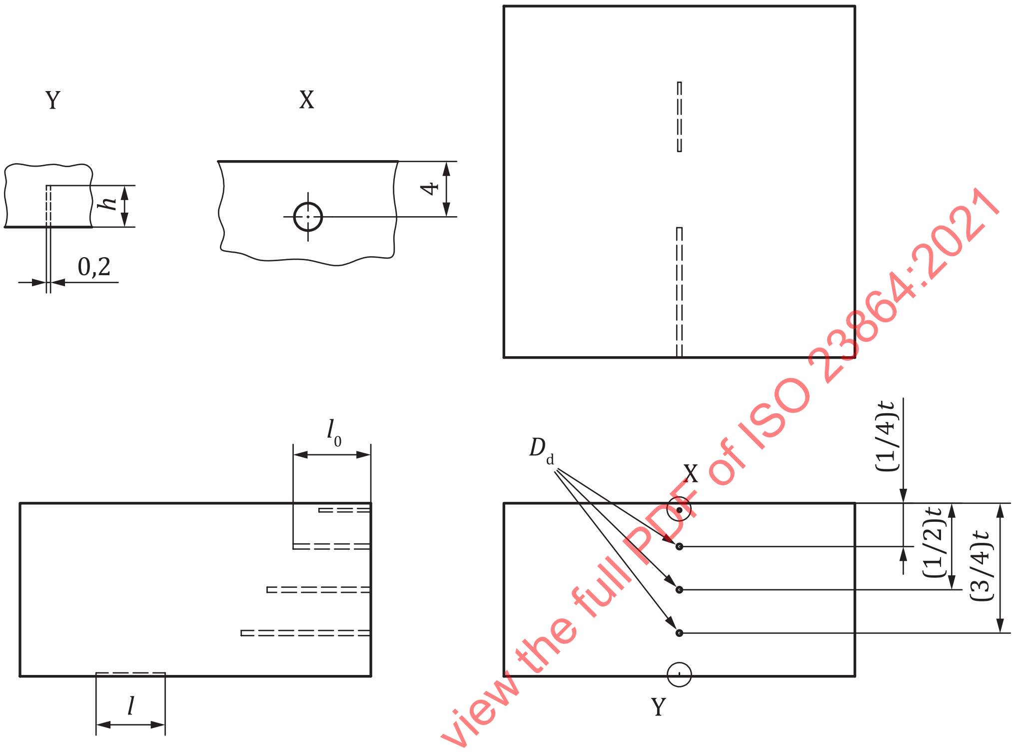
t thickness of block

Figure A.1 — Recommended reference block for testing level A

A.2.2 Testing level B

See Figure A.2.

Dimensions in millimetres



Key

D_d diameter of side-drilled hole
h depth of notch at the bottom
l length of notch at the bottom
l_0 length of side-drilled hole
t thickness of block

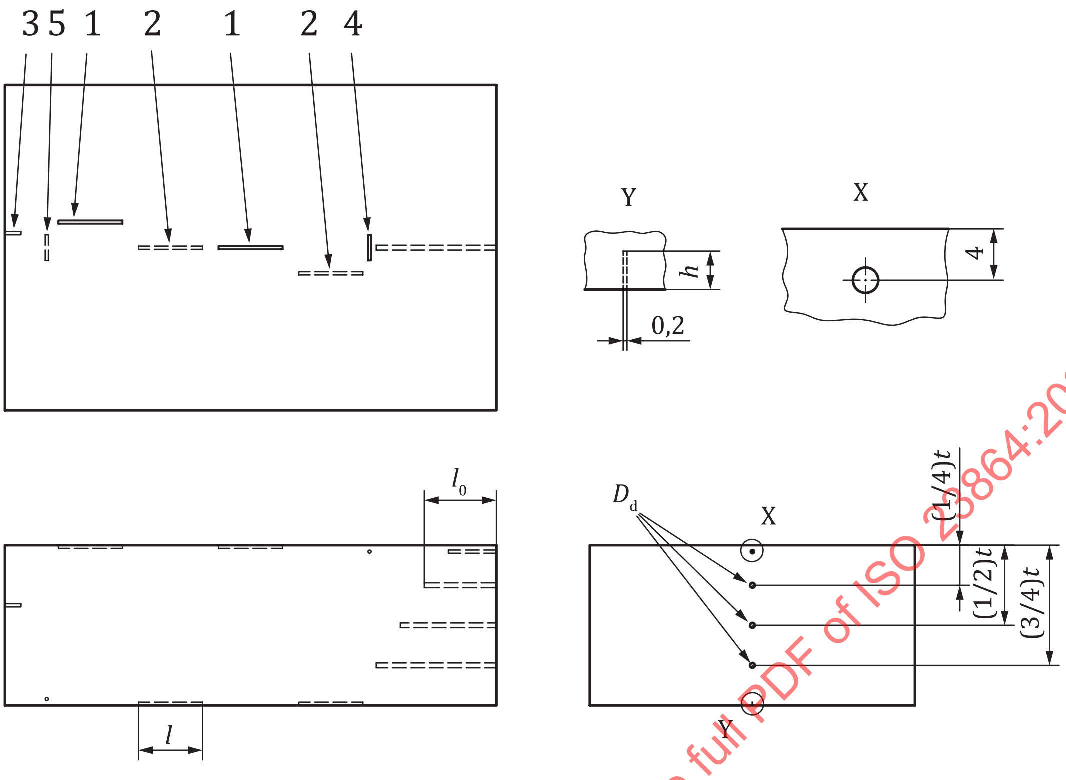
Figure A.2 — Recommended reference block for testing level B

Detail X shows a side-drilled hole located at 4 mm below the surface, with a diameter of 2 mm and a minimum length of 30 mm. Alternatively, a surface notch can be used with the same dimensions as described in Table A.1.

A.2.3 Testing level C

See Figure A.3.

Dimensions in millimetres



Key

D_d diameter of side-drilled hole

h depth of notch

l length of notches

l_0 length of side-drilled hole

t thickness of block

1 near-side surface notches

2 far-side surface notches

3 notch on imaginary weld bevel

If required by specification:

4 near-side surface transverse notch

5 far-side surface transverse notch

Figure A.3 — Recommended reference block for testing level C

Detail X shows a side-drilled hole located at 4 mm below the surface, of diameter 2 mm and minimum length 30 mm. Alternatively, a surface notch can be used with the same dimensions as described in Table A.1.

The notches 2 and 4 are positioned at the imaginary weld centreline. The notches 1 and 3 are positioned at the edges of the volume to be tested. Notch 5 is positioned on the imaginary weld bevel with an orientation of ±5° to the weld bevel. The dimensions and the location of notch 5 shall be as specified.

There should be a volume in the reference block which is kept free from artificial reflectors. The extent of this volume should exceed the sound beam width. This volume should be symmetrical about the weld centreline.

A.2.4 Testing level D

For testing level D, special blocks shall be made with the same configuration, base material properties, weld material properties, weld process and additional to the test blocks described for testing levels B and C. Additional reflectors shall be added.

A.2.5 Objects with thickness 3,2 mm to 8 mm

For testing objects with thickness 3,2 mm to 8 mm a reference block as shown in Figure A.4 may be used to:

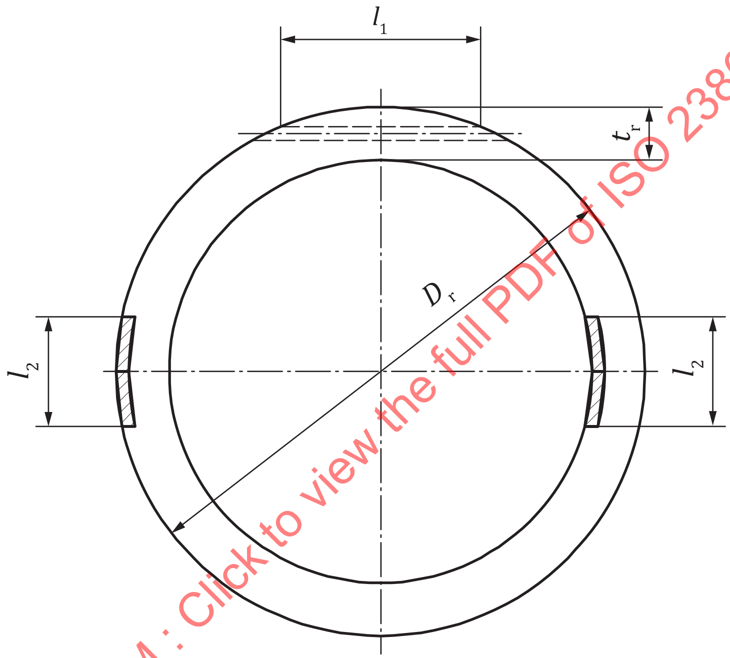
a) check the offset of probes;

b) check the testing volume;

c) adjust range and test sensitivity;

d) perform checking of the settings;

e) perform transfer correction if needed.



Key

D_r diameter of the reference block
t_r thickness of the reference block
l_1 length of side-drilled hole
l_2 length of inside and outside reference reflector

Figure A.4 — Typical reference block for circumferential welds 3,2 mm to 8 mm

At least 3 reflectors shall be implemented: 2 notches and a side-drilled hole at half thickness.

Annex B
(informative)

TFM images of typical discontinuities

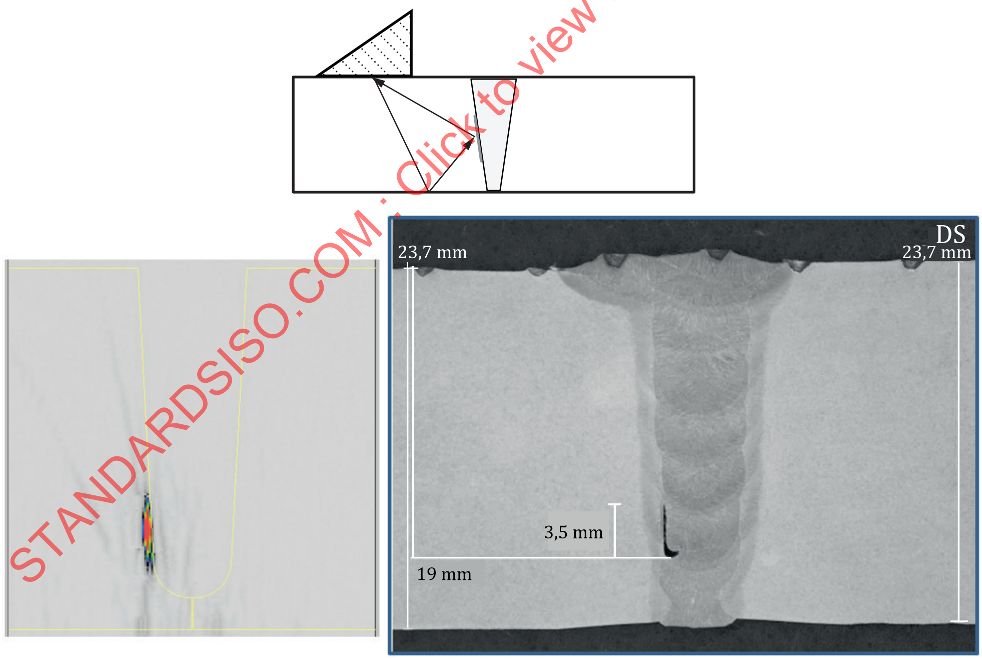
B.1 General

This annex gives examples of TFM images on typical weld discontinuities. For each example, a macrograph is given for comparison, and the used imaging path(s) is/are mentioned and shown in a sketch. The TFM images and macrographs have the same scale in horizontal and vertical direction and can be directly compared. The thickness of the object is given which gives an impression of the size of the ROI.

Evaluation of indications may not be possible based on a single imaging path, other imaging paths can give relevant additional information. The interpretation of TFM images requires skilled and experienced operators. Classification of indications in terms of discontinuity type is not always possible or required by specification.

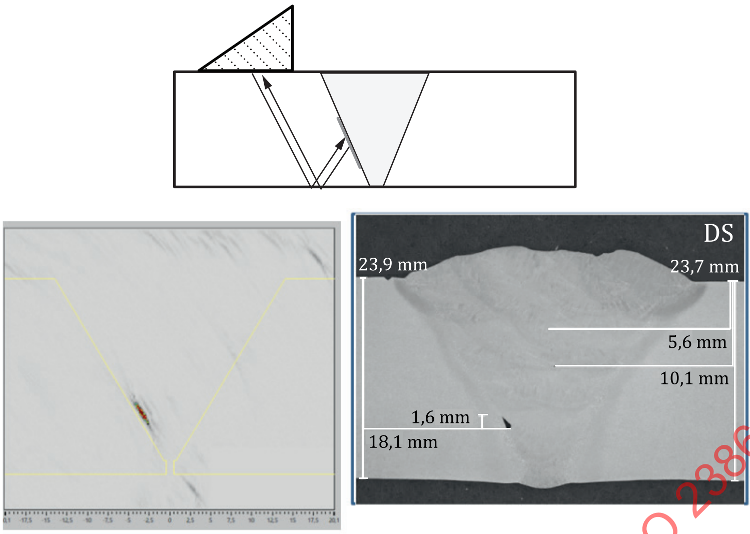
B.2 Examples of images

See Figures B.1 to B.8.

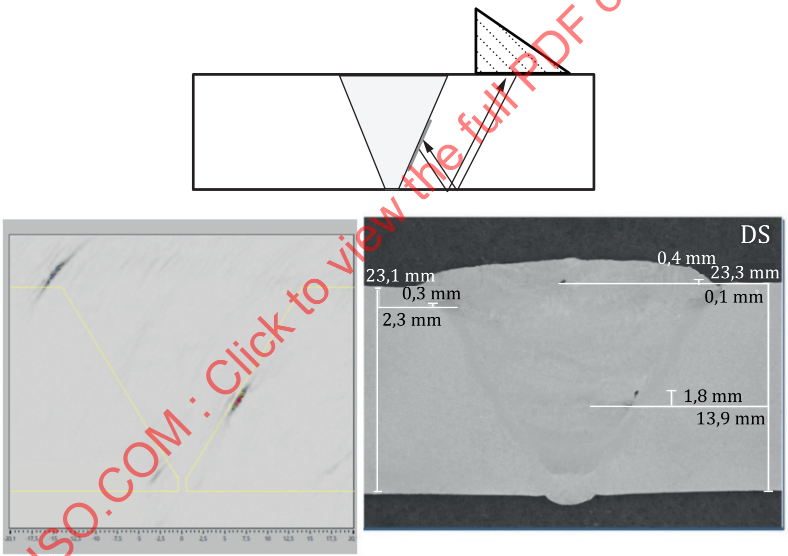


NOTE Image showing imaging path TT-T/T-TT (thickness 23 mm).

Figure B.1 — Example image of lack of fusion in weld with low-angle weld bevel

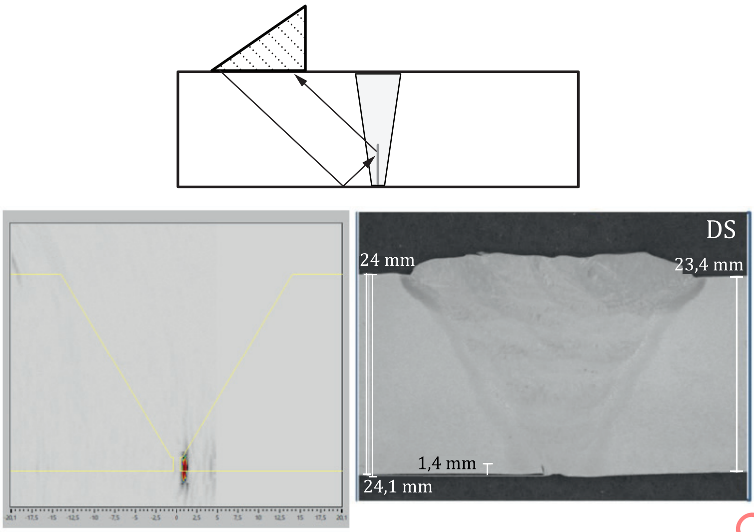


a) Indications detected by array on the left (TT-TT) (thickness 23 mm)

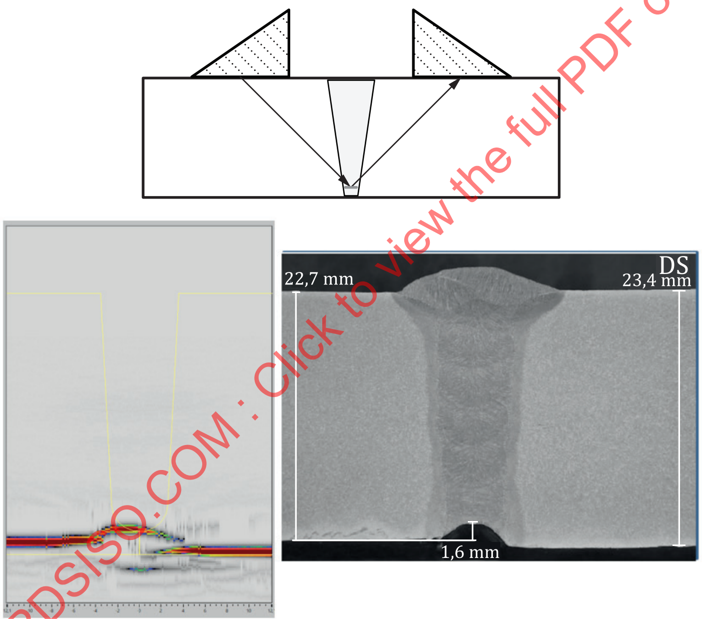


b) Indication detected by array on the right (TT-TT) (thickness 23 mm)

Figure B.2 — Example image of lack of fusion in a weld with high-angle weld bevel



a) Imaging path TT-T (indicating lack of root fusion) (thickness 23 mm)



b) Incomplete penetration (T-T using separate arrays) (thickness 23 mm)

Figure B.3 — Example image of lack of root fusion/incomplete penetration

