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Non-destructive testing — Ultrasonic testing — General use of full matrix capture/total focusing technique (FMC/TFM) and related technologies

Essais non destructifs — Contrôle par ultrasons — Utilisation générale de l'acquisition de la matrice intégrale/technique de focalisation en tous points (FMC/FTP) et de techniques associées

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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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 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*.

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 — Ultrasonic testing — General use of full matrix capture/total focusing technique (FMC/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 gives general provisions for applying ultrasonic testing with arrays using FMC/TFM techniques and related technologies. It is intended to promote the adoption of good practice either at the manufacturing stage or for in-service testing of existing installations or for repairs.

Some examples of applications considered in this document deal with characterization and sizing in damage assessment.

Materials considered are low-alloyed carbon steels and common aerospace grade aluminium and titanium alloys, provided they are homogeneous and isotropic, but some recommendations are given for other materials (e.g. austenitic ones).

This document does not include acceptance levels for discontinuities.

For the application of FMC/TFM to testing of welds, see ISO 23864.

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 16810, *Non-destructive testing — Ultrasonic testing — General principles*

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 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 23243 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
full matrix capture/total focusing technique
FMC/TFM
assembly of a data acquisition scheme and imaging scheme, whereby the acquisition scheme involves a full matrix capture, and the imaging scheme involves a total focusing technique, and where the data acquisition and imaging scheme may be performed with several similar technologies.

Note 1 to entry: TFM is often indicated as "total focusing method" but, in this document, the term "method" in NDT is reserved for applying a physical principle (see ISO 9712).

3.2
FMC/TFM setup
probe arrangement defined by probe characteristics (e.g. frequency, probe element size, wave mode), probe position, and the number of probes.

Note 1 to entry: Unless stated otherwise, in this document “TFM” and “FMC” refer to the techniques as defined in ISO 23243, and to all related technologies see for example Annex B and ISO 23243.

4 Principle of the technique

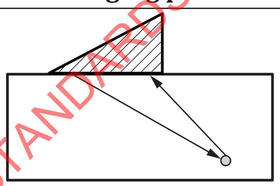
4.1 General

Both FMC/TFM and phased array ultrasonic testing (PAUT) use an array probe where each element of the array is independent of the others. Physical characteristics related to the propagation of waves from the elements of the array govern the capabilities of both techniques in a similar way. In standard PAUT, as in ISO 13588, the active aperture is used to generate sound beams for testing.

In comparison, the FMC/TFM approach typically uses the entire array in order to achieve the best possible focused imaging performance because for effective focusing the test volume should be within the near-field region of the array, which is maximized by using the entire array. In the PAUT technique, the beams can also be "focused" in a similar way to FMC/TFM by using large apertures or the entire array to create beams that concentrate the sound pressure to specific points, by ensuring that these focal points are within the near-field region of the aperture.

Various imaging paths as described in Table 1 may be used.

Table 1 — - Description of the imaging paths

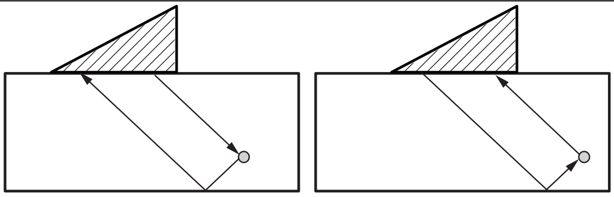
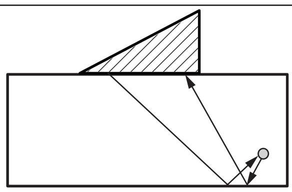
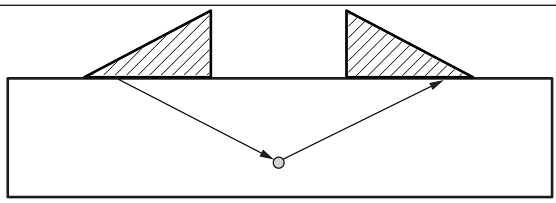
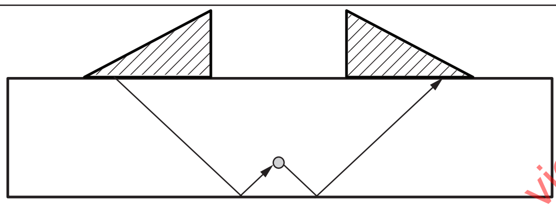
Imaging path	Examples	Description
	T-T L-L	transmitter path direct, receiver path direct

NOTE 1 All figures are schematic, not to scale. Due to the principle of reciprocity, transmitter and receiver can be swapped, meaning that the whole path can be followed in the opposite direction. The direction of the arrows for the paths shown in this table is arbitrary. Drawings are intended to illustrate the assumptions made on the imaging path for calculation of the image and do not intend to imply beam forming or focusing of ultrasonic waves.

NOTE 2 The use of indirect imaging paths, especially those aiming at producing an image representative of the reflectors shape, require an accurate assessment of the actual component physical properties, such as ultrasonic wave velocity, wall thickness or non-flat surfaces. This can be compensated for in post-processing or by using an adaptive imaging algorithm.

NOTE 3 L corresponds to longitudinal wave mode and T to transversal wave mode.

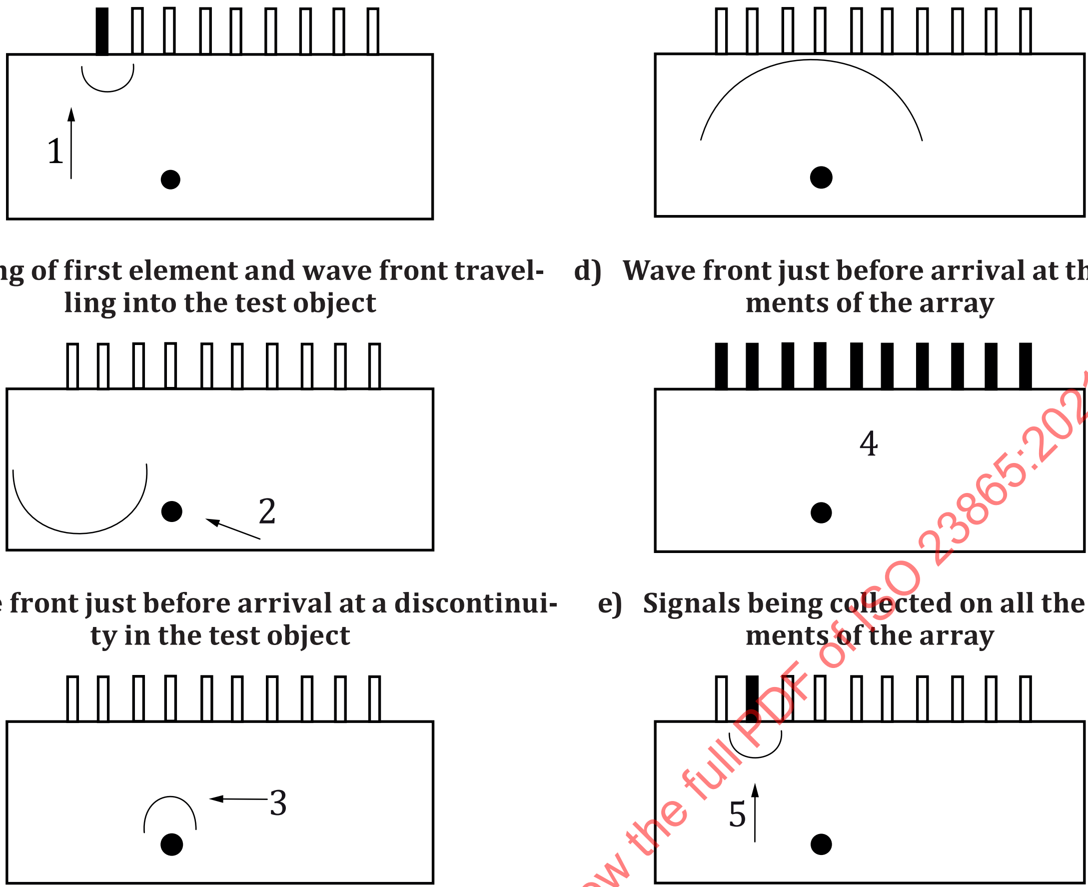
Table 1 *(continued)*

Imaging path	Examples	Description
 OR	T-TT, TT-T LL-L, L-LL LT-T, T-TL TT-L, L-TT	transmitter path direct, receiver path indirect or transmitter path indirect, receiver path direct
	TT-TT LL-LL TL-LT	transmitter path indirect, receiver path indirect
	L-L T-T	transmitter path direct, receiver path direct (using separate arrays with a known distance)
	TT-TT LL-LL TL-LT	transmitter path indirect, receiver path indirect (using separate arrays with a known distance)
NOTE 1 All figures are schematic, not to scale. Due to the principle of reciprocity, transmitter and receiver can be swapped, meaning that the whole path can be followed in the opposite direction. The direction of the arrows for the paths shown in this table is arbitrary. Drawings are intended to illustrate the assumptions made on the imaging path for calculation of the image and do not intend to imply beam forming or focusing of ultrasonic waves. NOTE 2 The use of indirect imaging paths, especially those aiming at producing an image representative of the reflectors shape, require an accurate assessment of the actual component physical properties, such as ultrasonic wave velocity, wall thickness or non-flat surfaces. This can be compensated for in post-processing or by using an adaptive imaging algorithm. NOTE 3 L corresponds to longitudinal wave mode and T to transversal wave mode.		

4.2 Comparison between FMC/TFM and PAUT

PAUT applies different time delays to the elements of the active aperture in order to control the sound beam within the test object. This results in a beam as governed by the constructive and destructive interference of the wavelets from each element of the active aperture. During the reception phase, the elementary signals are summed to give a single A-scan. In addition to being able to "steer" the beam through a range of angles, in PAUT each beam can also be controlled to focus the sound pressure within the near-field region of the active aperture.

In comparison, TFM is a post-processing or imaging technique applied to FMC signals that does not create beams within the test object during the transmission phase. Instead, the sound field transmitted into the component emanates from one element of the array and the echoes generated within the component due to this sound field are then recorded on all elements of the array, as illustrated in Figure 1. Successive firing of individual elements on the array and recording of resultant echoes on all elements is termed full matrix capture (FMC).



a) Firing of first element and wave front traveling into the test object

d) Wave front just before arrival at the elements of the array

b) Wave front just before arrival at a discontinuity in the test object

e) Signals being collected on all the elements of the array

c) Reflected or diffracted echo(es) from the discontinuity returning back in the direction of the array

f) Process continued by firing element 2 and repeated until the last element N of the array is fired

Key

1 wave front transmitted by element 1

2 discontinuity

3 wave front reflected or diffracted by the discontinuity

4 receiving elements

5 wave front transmitted by element 2

Figure 1 — Typical example of points in time describing the FMC data collection process

The FMC data can then be processed by algorithms that operate on the data matrix to create images of the echoes from the component. Total focusing technique (TFM) is a term used to describe one such algorithm that applies calculated delay laws to the FMC data in order to focus the sound on many points within a defined region of interest (ROI) (see Annex B for details). This imaging phase (where TFM is applied on the FMC data) is computationally intensive but modern systems are able to achieve near real-time imaging performance.

A more detailed comparison is given in Annex A.

5 Requirements for surface condition and couplant

Care shall be taken that the surface condition meets at least the requirements given in ISO 16810. Since, typically, only individual elements are used as transmitter and any diffracted signal can also be weak, the degradation of signal quality due to poor surface condition has a severe impact on testing reliability.

Different coupling media can be used but their type shall be compatible with the materials to be examined. Examples are water (possibly containing an agent, e.g. wetting, anti-freeze, corrosion inhibitor), contact paste, oil, grease, cellulose paste containing water, etc.

The characteristics of the coupling medium shall remain constant throughout the examination. It shall be suitable for the temperature range in which it will be used.

6 Information required prior to testing

6.1 General

ISO 18563-3 gives useful information.

6.2 Items to define prior to procedure development

Before any testing can begin, the operator shall have access to all the information as specified below:

a) purpose and extent of testing;

b) reporting criteria;

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

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

e) geometrical characteristics (especially when reflection is used);

f) requirements for access and surface conditions and temperature;

g) time of testing relative to any heat treatment (if any);

h) acceptance criteria and sizing methodologies shall be defined by specification and provided before testing (to be adapted when recommendations for the application cases are written).

In case of any suspicion of anisotropy in the material to be tested, special care shall be taken.

7 Requirements for test personnel

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

In addition to general knowledge of ultrasonic testing, the operators shall be familiar with and have practical experience in the use of FMC/TFM technique or related technology.

Specific training and examination shall be performed with the finalized ultrasonic testing procedures and selected ultrasonic testing equipment on representative samples containing natural or artificial reflectors similar to those expected. These training and examination results shall be documented.

8 Requirements for test equipment

8.1 General

The FMC acquisition process requires a system able to fire the elements one by one and collect the individual element signals from the array probe. Other processes may be used including adaptive processes (see Annex B).

The TFM process can require a fast processing capability and a large memory capacity to handle the large amount of data from the FMC acquisition. Alternative processes may be applied using smaller memory capacity (e.g. based on plane wave imaging, PWI).

8.2 Instrument

FMC/TFM instruments may display images of the same type as conventional PA instruments (B-Scan, C-Scan, D-Scan) but may also provide other types of images.

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

The ultrasonic 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 the length of the acquired A-scan is sufficient, considering the imaging path that will be processed or post-processed. It is recommended that the bandwidth of the ultrasonic system 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 data visualized after a TFM process is generally a region of interest (ROI) which is a grid where each grid point represents the computed amplitude (see 4.2 and Annex B). Grids are usually regular, e.g. rectangular, but can be arbitrary (even 3D). Regular grids are usually preferred (e.g. to allow optimization in order to enhance the number of images per second).

The grid spacing shall be selected small enough to be able to detect the relevant discontinuities. The minimum spatial resolution of data points within the image (i.e. grid point spacing) shall be chosen such that the amplitude of a reference reflector is stable within a specified tolerance on small deviations in the probe position. Annex C contains guidance on validation of the amplitude stability.

8.3 Probes

Any linear or matrix array probe can be used for FMC acquisition, but this document is limited to the use of linear phased array probe. Ultrasonic arrays used for the FMC/TFM testing shall be in accordance with the requirements of ISO 18563-2.

The TFM process requires information on the element positions relative to the test object, including details of the delay line or wedge, in order to compute the times of flight associated to the imaging path(s).

Probes in direct contact to the test object can be used but also delay lines, angled wedges or immersion can be used depending on the application. Required details of the delay line or wedge include the type, dimensions, angle and sound velocity.

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 aperture and elevation 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.

Typically, these requirements are fulfilled by a probe with relative bandwidth >60 % and an element pitch that is smaller than half the wavelength as determined in the wedge (or in the part under testing when no wedge is used).

The number of dead elements on the active aperture should be less than or equal to 1 out of 16 and any dead elements are not allowed to be adjacent to each other. If this criterion is not met, the probe may be used provided appropriate technical justification is given.

8.4 Scanning mechanisms

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

The scan increment setting in the primary scanning direction is dependent on the thickness to be examined. Recommended values are given in Table 2.

Other values may be used provided appropriate technical justification is provided.

The scan increment settings perpendicular to the primary scanning direction, when applicable, shall be chosen in order to ensure the coverage of the test volume.

An additional function of scanning mechanisms is to provide position information in order to enable the generation of position-related FMC/TFM images.

Table 2 — Scan increment values in the primary scanning direction in accordance with thickness

Dimensions in millimetres

Thickness t	Scan increment
$t \leq 6$	0,5
$6 < t \leq 10$	1
$10 < t \leq 150$	2
$t > 150$	3

Scanning mechanisms in FMC/TFM can either be motorized or manually driven. They shall be guided by means of a suitable guiding mechanism. The tolerances for the probe position depend on the application and it shall be given in the written test procedure.

The scanning speed shall be suitable for the equipment used in order to avoid loss of data.

8.5 Sampling frequency

The sampling frequency of the A-scans should be at least five times the nominal centre frequency of the probe. If interpolation (up-sampling) of the A-scans is used, the hardware sampling frequency may be as low as three times the upper cut-off frequency (-6 dB) of the probe.

The theoretical limit according to the Nyquist sampling theorem is twice the upper frequency of the signal, but additional margin should be provided for non-ideal filters before analogue-to-digital conversion.

8.6 Data processing

The processing of A-scan data based on time of flight (from the transmitter to an image point and back to the receiver) is generally referred to as imaging. This is the basis of TFM. Optionally, the processing algorithms can also take into account physical parameters to improve the quality of the resulting image, like directivity, divergence, attenuation, reflectivity, transmission coefficients and apodization.

A detailed description of TFM is given in 4.2 and Annex B. Descriptions of related technologies are given in ISO 23243 and Annex B, such as sampling phased array (SPA), plane wave imaging (PWI) and inverse wave field extrapolation (IWEX).

Once the data has been processed into an image, additional image processing may be applied afterwards for further optimization/visualization.

8.7 Evaluation of TFM indications

The recommended sizing methods are:

a) extraction of signals scattered (diffracted) from different points on the discontinuity and deducing the extent of the discontinuity based on images of the diffracted signals;

b) using amplitude drop with respect to the maximum TFM indication response to establish the extent of the discontinuity.

In accordance with the application requirements, other sizing methods may be used.

9 Benefits of various imaging paths

By including boundary reflections in the path from transmitter to receiver, discontinuities in the ROI can be imaged from different directions using both reflection and diffraction signals, which can improve the performance and reliability of testing.

Volumetric discontinuities resulting in reflection (in many directions) and edges of discontinuities resulting in diffraction (in many directions) are typically detected with each imaging path that covers the region of the discontinuity.

In general, discontinuities with an orientation (planar discontinuities) are best detected with imaging paths (see Table 3) where the incident angle and reflected angle on the discontinuity are:

a) (about) perpendicular to the discontinuity orientation;

b) (about) symmetric to the normal direction of the discontinuity; or

c) according to Snell's law if mode conversion occurs at the discontinuity.

Table 3 — Advantages of different imaging paths

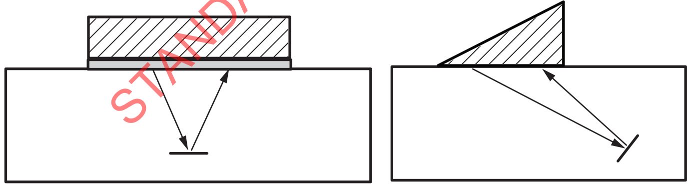
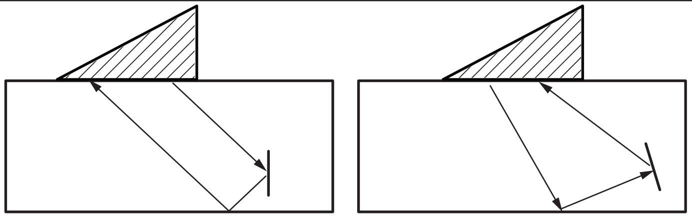
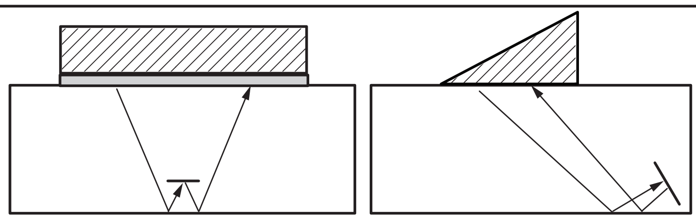
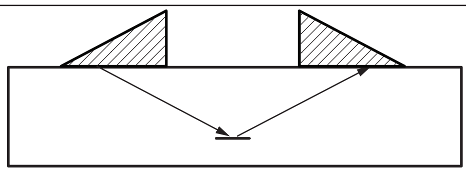
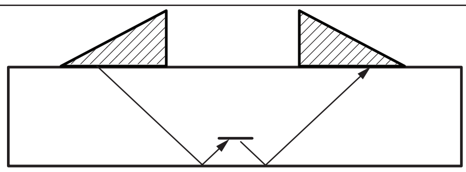
Imaging path	Orientation of discontinuities for reflection
	Discontinuities with (near) horizontal orientation. Discontinuities with other orientations depending on incident and reflected angles.
	Discontinuities with (near) vertical orientation. Discontinuities with other orientations if mode conversion occurs in the path.

Table 3 *(continued)*

Imaging path	Orientation of discontinuities for reflection
	Discontinuities with (near) horizontal orientation. Discontinuities with other orientations depending on incident and reflected angles.
	Discontinuities with (near) horizontal orientation.
	Discontinuities with (near) horizontal orientation.

10 Preparation for testing

10.1 General

The purpose of the testing shall be defined by specification. Based on this, the test volume to be inspected shall be determined.

The surface temperature of the object under test shall be in the range 0 °C to 50 °C. For temperatures outside this range, the suitability of the equipment and couplant shall be verified.

Imaging approaches such as TFM require knowledge of a number of parameters related to the measurement system, array, setup geometry and material properties. This clause provides an overview of parameters considered relevant for imaging.

10.2 System checking

System check/setup shall take into account the following:

a) element sensitivity, dead elements and amplitude balancing may be applied if required;

b) wedge parameters (velocity, angle, dimensions).

Any corrections due to these items shall be reported as specified in the test procedure.

The minimum items to be checked are listed below:

a) calibration checking;

b) coverage checking;

c) sensitivity checking and settings;

d) settings to be taken into account to achieve an appropriate level of detection;

e) sizing/characterization (surfaces, body) assessment;

f) aspects to be defined in a procedure;

g) calibration/reference/qualification blocks;

h) aspects to set in a report.

Additional aspects can need to be addressed depending on application cases.

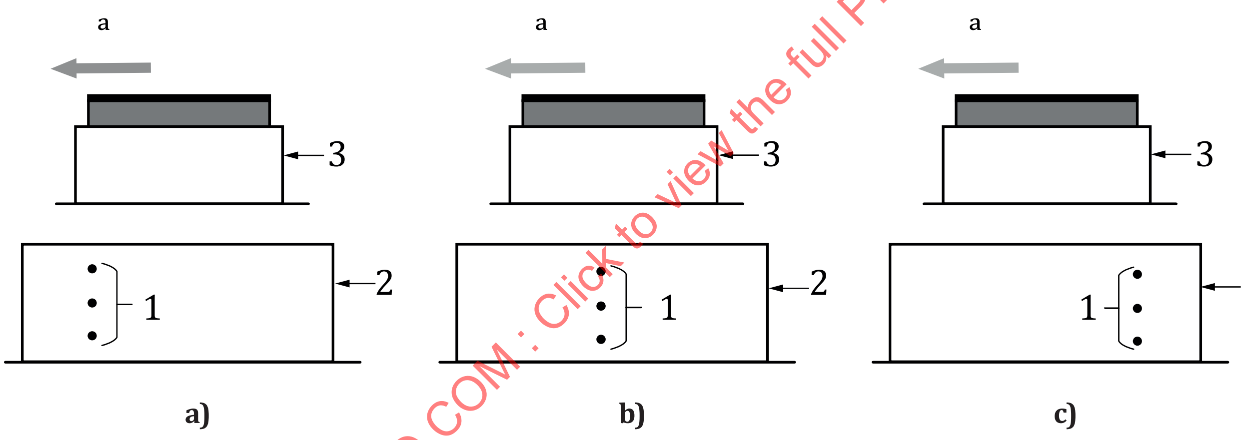
10.3 Sensitivity correction

For general applications, sensitivity can be corrected using 3 mm diameter SDHs (side drilled holes), for example in a calibration block (e.g. ISO 19675).

If required for the application, and if the processing does not take all propagation effects into account, then amplitude correction may be applied. Amplitude calibration for TFM is similar to time corrected gain (TCG) or angle corrected gain (ACG) in PAUT calibration: the probe is moved over a set of SDHs located at different depths in a reference block as defined in Table 4.

NOTE Simulated sensitivity corrections are possible.

The amplitude on each SDH is recorded for a horizontal line in the ROI, over its complete width, by moving the probe over the SDHs as shown in Figure 2. A correction is then established by determining the gain necessary to adjust the response of each SDH to the desired level, along the horizontal line in the ROI corresponding to the position of each SDH. Gain levels for the points in the vertical direction between the horizontal lines corresponding to the SDHs are derived by interpolation.



Key

1 side drilled holes

2 ROI

3 probe

a Probe movement.

Figure 2 — Illustration of probe movement over SDHs for sensitivity correction

Any reference block with a sufficient number of SDHs divided equally over the height of the ROI in accordance with Table 4 may be used.

Table 4 — Number of SDH to use in accordance with ROI height

ROI height, *h* mm	**Minimum number of SDH**	**Depth difference between 2 adjacent SDH**
≤ 10	1	N/A
10 < *h* ≤ 40	3	N/A
>40	N/A	<20 % *h*

10.4 Sensitivity setting

If requested, the test sensitivity shall be set/verified on a reference reflector that is representative of the discontinuities to be detected.

If multiple imaging paths (TTT, TTL, etc.) are used, then the sensitivity needs to be calibrated individually. For in-service situations, this can be difficult without a suitable reference piece. Depending on the application, TFM indications stemming from the geometry or the noise level of the test object can be used as well.

10.5 Grid verification

Guidance for grid verification is given in Annex C.

10.6 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, Ra, 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 good imaging results.

10.7 Couplant

In order to generate good 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.

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.

11 Test procedure

For any ultrasonic examination, an examination procedure shall be established. In addition to the requirements stated in this document, at least the following details shall be included, as applicable:

a) description of the products to be examined;

b) reference documents;

c) qualification and certification of examination personnel;

d) state of examination object;

e) test volume;

f) testing techniques;

g) preparation of scanning surfaces;

h) coupling medium;

i) description of examination equipment;

j) environmental conditions;

k) reference and/or calibration blocks, including description of the reflectors;

l) calibration and settings;

m) imaging path(s) to be used;

n) scan plan;

o) description and sequence of examination operations;

p) evaluation and recording levels;

q) characterization of imperfections;

r) acceptance criteria;

s) examination report.

Specific conditions of application and use of the FMC/TFM technique depend on the type of product examined and any specific requirements shall be described in written examination procedures.

The objective of the testing shall be agreed.

For in-service testing, the effectiveness of the procedure on test blocks having natural discontinuities should be verified.

Information regarding settings and examples of images for different flaw types are given in Annex D.

For weld testing, ISO 23864 applies.

A satisfactory procedure verification in accordance with the specification required shall take place before the first inspection. This verification includes:

a) detection of all required reflectors;

b) classification and sizing capability;

c) proof of coverage in depth and width.

12 Data storage

Compared to PAUT, FMC/TFM 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). 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 constructed images as well as the applied imaging parameters and processing steps shall be stored on a digital storage medium such as hard disk or IT server and shall be kept for later reference.

13 Interpretation and analysis of TFM images

13.1 General

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

a) assess the quality of the TFM images;

b) identify relevant TFM indications;

c) determine location and size as specified;

d) classify relevant TFM indications as specified;

e) evaluate against acceptance criteria.

13.2 Assessing the quality of TFM images

An FMC/TFM test shall be carried out such that satisfactory images are generated that can be interpreted with confidence. Satisfactory images are defined by appropriate:

a) coupling;

b) ROI settings;

c) sensitivity settings;

d) signal-to-noise ratio;

e) saturation indicator;

f) data acquisition;

g) tuning of processing parameters.

If the signal to be evaluated is saturated, it shall be rescanned if the amplitude drop measuring method has been chosen.

Where encoded scanning is performed, a maximum of 5 % of the total number of scan points collected in one single scan may be missed but no adjacent points shall be missed.

Assessing the quality of FMC/TFM images requires skilled and experienced operators (see Clause 7). The written test procedure shall give requirements depending on the application whether non-satisfactory images require new data acquisition (re-scan).

13.3 Identification of relevant TFM indications

The FMC/TFM technique images both discontinuities and geometric features of the test object.

In order to identify TFM indications of geometric features, detailed knowledge of the test object is necessary.

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

The written test procedure shall give details for the evaluation of TFM indications depending on the application.

14 Test report

FMC/TFM test reports shall comply with the requirements given in ISO 16810, as applicable.

In addition, FMC/TFM testing reports shall contain the following information:

a) description of the test specimen, any reference and/or test blocks;

b) description of FMC/TFM instrument used, including scanning mechanisms;

c) probe type, frequency, number and size of elements, material and angle(s) of any wedge (or in water for immersion technique), orientation and position with respect to a reference line;

d) plotted images of at least those locations where relevant TFM indications have been detected;

e) results of checking resolution, coverage and grid verification (see Annex C).

Relevant settings of the FMC/TFM technique shall be documented. This should include:

a) sensitivity settings;

b) acquisition process;

c) imaging process;

d) details of the ROI;

e) imaging path(s) used;

f) scan plan;

g) characterization and sizing methodology.

15 Typical influences and compensation mechanisms

Wall thickness variations can lead to images that use imaging paths with a reflection at the back wall to show discontinuities out of focus and/or in the wrong location. This can be compensated for in post-processing or by using an adaptive imaging algorithm (see B.5).

Anisotropy caused by an elongated grain structure, e.g. resulting from rolling of steel, causes discontinuities to be displayed out of focus. This may be compensated for by limiting the aperture to sound path with a low sound angle, by using angle-dependent sound velocities or with adaptive algorithms.

Irregular geometries resulting from manufacturing and/or welding method, causing the surface to be non-flat causes discontinuities to be displayed out of focus if the ultrasound is reflected at, or transmitted through, this surface. This can be compensated for by using an adaptive algorithm (see B.5).

A potential issue with FMC is that, due to only one array element being pulsed at a time, a limited amount of energy is emitted by the probe. The consequence is that this energy can diffuse into materials that are attenuative and/or very thick and not penetrate to flaw locations. This may be compensated for by using probes that are more appropriate or an alternative acquisition scheme that uses more transmitting elements (see Annex B for possible alternatives).

When the temperature is outside the range specified in 10.1, correct imaging performance shall be established using a reference block of the same material as the component under test, containing SDH targets within the required ROI and with the reference block brought to the same temperature as the component under test.

Other ultrasonic techniques are also impacted by these properties. However, the influence can be less recognizable, e.g. when only using A-scan display. By appropriately accounting for these influences FMC/TFM can allow for a high testing quality in situations where this would not be possible with other ultrasonic techniques.

Annex A
(informative)

Comparison of FMC/TFM technique with conventional phased array ultrasonic testing (PAUT)

A.1 Advantages and disadvantages

Tables A.1 and A.2 present the advantages and disadvantages of the FMC/TFM technique in comparison to PAUT, respectively. Table A.1 highlights application cases where FMC/TFM can offer significant advantages over PAUT.

Table A.1 — Advantages of FMC/TFM over PAUT for ultrasonic testing

Aspect	PAUT	FMC/TFM	Applications for FMC/TFM
Focusing	Beams can be focused to a limited locus, usually a constant depth, projected plane or a constant ultrasonic distance along the beams.	All points (defined by a high-resolution grid) within the ROI can be focused during the imaging process using TFM.	Sizing discontinuities during testing, in particular the detection of diffracted echoes from crack tips.
Spatial resolution (ability to resolve two or several closely spaced reflectors)	If unfocused beams are used then the spatial resolution of PAUT is poor, with the primary aim being detection of discontinuities rather than sizing. If focusing is used, then good spatial resolution can be achieved but limited to the locus of focusing.	In a TFM image, optimal resolution is achieved at all points within a well-conditioned ROI. Point reflectors in the ROI, when spaced apart larger than the grid resolution, image well (without large arcs) and can be resolved.	Sizing discontinuities during testing, in particular the ability to better characterize their nature.
Relative insensitivity to incidence angle onto discontinuities, discontinuities or geometric features	As the transmitted beams have well-defined directions, the response from the discontinuities on which they are incident is dependent on the angle of incidence, with maximum reflected energy being for specular incidence.	Since the image is created by summing multiple transmit-receive paths from the elements of the array, compared to PAUT there is less sensitivity on the orientation of the discontinuity in the ROI.	Improved detection of directional (for example, planar crack-like) discontinuity in or adjacent to welds. Improved detection of pitting corrosion and accurate mapping of general thickness loss.
Wave mode velocity	The velocity of the wave mode needs to be accurately input for correct calculation of the delay laws for accurate plotting of echoes.	Velocities can be changed during post-processing after data collection and, hence, incorrect assumptions can be rectified without re-inspecting on site.	Accounting for temperature variations in the component. Advanced imaging of austenitic materials subject to anisotropy.
Component geometry	The geometric makeup of the testing setup needs to be accurately input to the system for correct calculation of the delay laws.	Geometric assumptions – regarding the system (e.g. wedge) and the component – can be modified, and the same data re-processed.	Adapting to scanning surface variations. This variation can be gentle curvature or rougher conditions but there are physical limitations.

Table A.1 *(continued)*

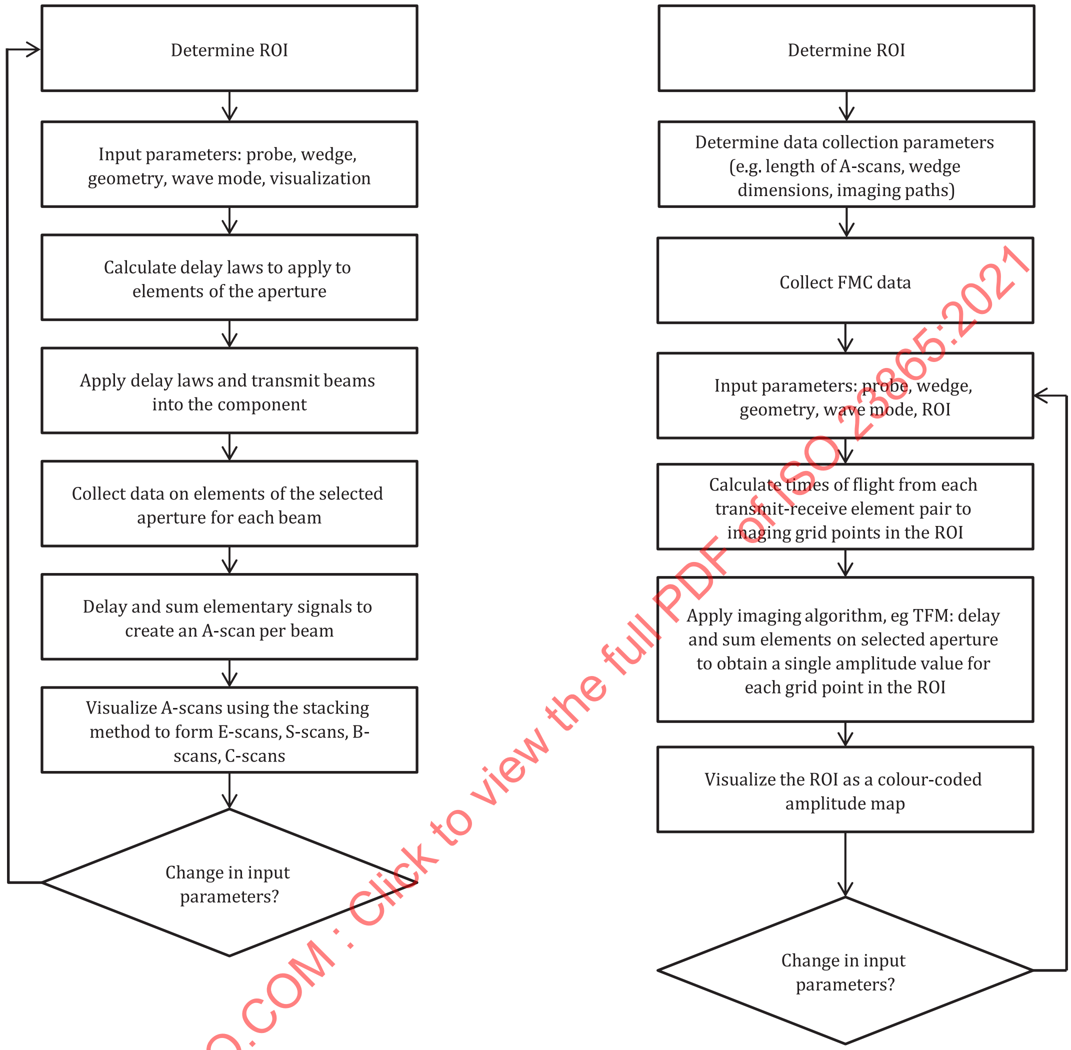
Aspect	PAUT	FMC/TFM	Applications for FMC/TFM
Dead zone **(region beneath the scanning surface/ front wall echo)**	Generally, large dead zones similar to all pulse - echo testing using beams where the receive direction is identical to the transmit direction.	Multiple transmit-receive paths between elements of the aperture spread over a much larger area of the front wall leads to smaller dead zones in the image.	Detection of discontinuities close to the scanning surface and improved capability to inspect components of smaller thickness.

Table A.2 shows possible disadvantage of FMC/TFM at present. As mentioned in the comments column, many of these disadvantages may not be an issue in the future as rapid advancements are ongoing.

Table A.2 — Disadvantages of FMC/TFM over PAUT for ultrasonic testing

Aspect	PAUT	FMC/TFM	Comment
Data file size	Data files sizes are similar to automated conventional UT and can be economically handled and archived using modern computing systems.	Data file sizes are orders of magnitude larger than PAUT and require increased processing capability and large capacity storage from the computing system.	The large FMC data file can be discarded after processing but this negates many of the advantages. Digital technology will likely outpace this limitation.
Operator training, certification and competency	Certified training courses are widely available and increasing acceptance of PAUT by industry is leading to personnel with sufficient exposure to gain good, wide competency.	No certified training presently available. Theoretical aspects of PAUT courses need modification for FMC/TFM but practical aspects can utilize similar probes and specimens for training.	FMC/TFM is considered an emerging area but operator exposure is increasing, which will lead to greater levels of competency in specific areas of application where FMC/TFM offers improved capability.
Instrumentation	Typically make use of multiplexers in order to address more elements than the available number of independent on-board pulser-receiver units.	Typically, use many independent pulser-receiver units that address array probes with many elements in order to increase near-field regions for effective focusing.	Viable, field-deployable equipment are available in the market and more are being designed for industry to be able to make an economic case for choosing FMC-TFM.
Unknown/variable geometry of component being inspected	When using beams, incorrect knowledge of component geometry – particularly when the back wall may not be parallel to the top surface when relying on a skipping technique – can lead to the echoes from component geometry and/or discontinuities, plotting incorrectly and/or with reduced echo amplitudes.	Accurate knowledge of geometry – in particular when using skipping from surfaces such as back walls – is critical for the imaging algorithms that implement summing of elementary signals based on times-of- flight. When there is discrepancy between reality and assumptions in geometry, there can be significant degradation in imaging performance.	Techniques to verify local geometrical variations should be implemented when using imaging algorithms that rely on reflection from the geometry. The influence of geometry and correctly accounting for its variation is illustrated well by the improvements achieved when using Adaptive TFM (ATFM) approach to varying top surface profiles.
Highly attenuative materials	Beams generated using a number of elements in an aperture can penetrate longer distances into attenuative materials by generating high sound pressures.	The sound pressure from individual transmitting elements during the FMC process can be attenuated in such materials, leading to poor imaging performance.	The nature of attenuative materials and the presence of anisotropy or scattering agents (such as coarse grains) can lead to significant degradation of all forms of ultrasonic testing.

Figure A.1 illustrates the core operating concepts behind PAUT [Figure A.1 a)] and FMC/TFM [Figure A.1 b)], highlighting the point at which data from the component is collected. This is the key advantage that FMC based testing has: it allows the technique to be created after the act of data collection. This offers significant economic advantages to industry, allowing for future reassessments and monitoring of a holistic record of the component that was inspected.



a) PAUT b) FMC/TFM

Figure A.1 — Illustration of the core operating concepts

Annex B
(informative)

FMC/TFM and alternative acquisition and imaging techniques

B.1 General

The scope of this document allows for alternatives to both the data collection scheme and the imaging scheme, together making up the technique. This annex gives a description of the basic FMC/TFM technique and some alternatives.

Due to historical reasons, the naming of the acquisition schemes and imaging schemes is not always logical or does not follow the conventions used in NDT, where a method denotes the physical measurement principle (e.g. ultrasonic testing) and a technique is the implementation of the physical measurement principle (e.g. pulse–echo technique, immersion technique). An example of such an inconsistency is the naming of total focussing method, which should have been a technique in accordance with ISO naming conventions. Another example is plane wave imaging, which is an acquisition scheme in the context of this document, and not an imaging scheme.

Alternatives to the acquisition scheme treated in this annex include half-matrix capture (HMC), sparse matrix capture (SMC), plane wave imaging (PWI) and virtual source aperture (VSA). Alternatives to the imaging scheme include adaptive TFM (ATFM) and TFM over multiple imaging paths. Additionally, the relationship to techniques that were historically developed independently from TFM, but are very similar, such as inverse wavefield extrapolation (IWEX) and sampling phased array (SPA), is mentioned.

B.2 FMC/TFM acquisition and imaging process

B.2.1 FMC acquisition process

As explained in 4.2, FMC consists of recording all the signals corresponding to all the possible pairs of transmitting and receiving elements on the array. To do that, each element is successively fired and at each step, the signals received on all the active elements are recorded. The outcome of this operation is the "full matrix" of the N^2 signals $Si,j(t)$ where (i,j) denotes the transmitter-receiver pair of elements and N is the number of elements of the array.

In the case of FMC acquisition, the acquired signals in one probe position are the $N \times N$ signals $Si,j(t)$ corresponding to the $N \times N$ pairs (i,j) of transmitter-receiver elements on the array.

B.2.2 TFM imaging process

Amongst the different schemes that can be proposed for imaging FMC data, the TFM algorithm is most widely used. This processing algorithm is based on delay and sum processing. The basic idea is to sum echoes arising from discontinuities coherently in order to maximize amplitudes where discontinuities are located. Thus, the signals are synthetically focused on a grid of points constituting the imaged zone. The output is a map of amplitudes, which are higher if there is correlation between echoes from the different signals. This approach originates from synthetic aperture radar, and it was initially introduced for conventional ultrasonic testing by the synthetic aperture focusing technique (SAFT).

Different names and acronyms have been used in the literature to designate array imaging based on this synthetic focusing algorithm, e.g. multi SAFT, IWEX, SPA. The acronym TFM can refer to the processing algorithm itself independently of the type of acquisition (FMC or others) carried out with the array. That means that the TFM algorithm can be applied to various acquisitions and not only to FMC.

The TFM algorithm applied to FMC is carried out in 2 steps.

a) Computation step: the times of flight t_{ij}(P) are calculated by considering geometrical acoustic paths (rays verifying Snell-Descartes laws). t_{ij}(P) = $T_{i\mathrm{P}}$ + $T_{j\mathrm{P}}$ where $T_{i\mathrm{P}}$ (respectively, $T_{j\mathrm{P}}$) is the time corresponding to the ray linking the centre of the element i (respectively, j) to grid point P. The small size of the elements in practice makes this simple geometrical model good enough for practical applications.

b) Summation step: the amplitude at points P of the image are calculated by summation of the $s_{i,j}$ ($T_{i\mathrm{P}}$ + $T_{j\mathrm{P}}$). The image intensity at each grid point is given by Formula (B.1).

$$I(\mathrm{P})=\sum_{i=1}^{N}\sum_{j=1}^{N} s_{ij}\left(T_{i\mathrm{P}}+T_{j\mathrm{P}}\right). \qquad \text{(B.1)}$$

Note that beyond the general form of the algorithm, variations can exist that mainly concern:

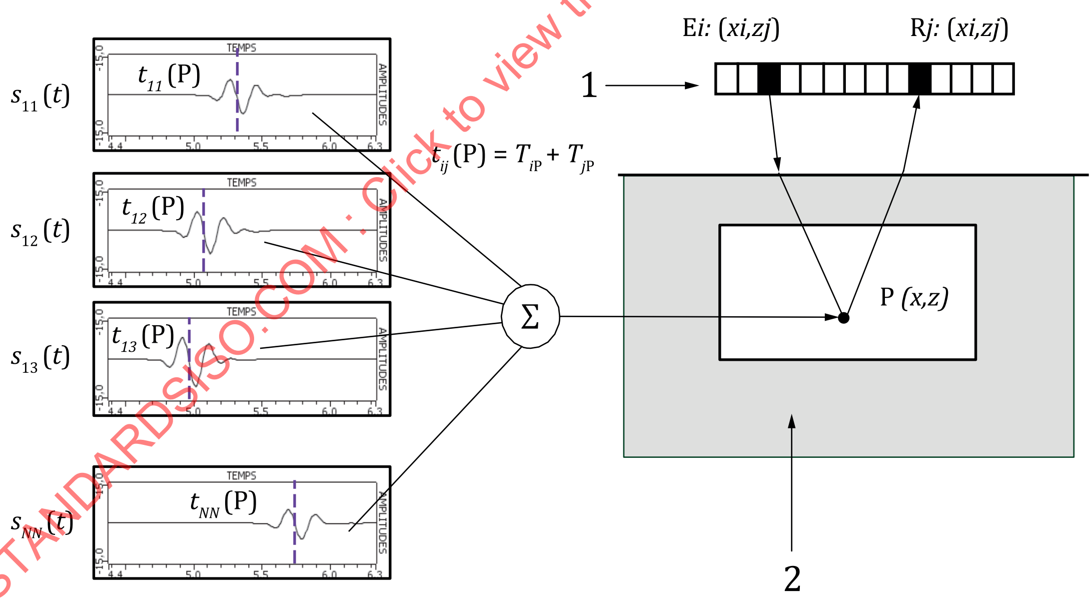
a) the numerical scheme used to compute the times of flight;

b) the implementation scheduling (different versions and optimizations related to the implementation in software/firmware of the test equipment);

c) the grid of computation points and the interpolation between these points;

d) the possibility to sum the amplitudes after signal processing;

e) the option to assign different weighting factors to the contributions of A-scans to one image point (e.g. IWEX).



a) Acquisition

Full matrix capture : $N \times N$ signals, $s_{ij}(t)$

b) Processing

Sum of the amplitudes of the captured signals at the computed times of flight, t_{ij}(P)

Key

1 N elements

2 image grid

Figure B.1 — TFM processing applied to FMC acquisition

B.3 Alternative acquisition scheme to FMC

B.3.1 General

Alternative acquisition schemes to FMC may be used. A different (typically smaller) set of signals is collected and processed in the same way as FMC signals are. The objective is to reduce the processing time by reducing the number of signals to be processed or to enhance the signal-to-noise-ratio (S/N).

Three main ways can be considered (see B.3.2 to B.3.4).

B.3.2 Acquisition of a subset of the full matrix

A subset of the full matrix of signals may be acquired by selecting fewer transmitter-receiver pairs as follows:

a) half-matrix capture (HMC): acquisition of only half of the signals by considering the redundancy of pairs of elements due to transmission-reception reciprocity. This technique leads to $N*(N+1)/2$ A-scans without (theoretically) loss of acquired information. Note that the S/N of the resulting image may be lower than for an image obtained from full matrix capture;

b) synthetic aperture focusing technique (SAFT) capture: called by analogy with the SAFT technique this scheme consists in acquiring only the signals S_{ii} of the matrix corresponding to the same transmitter and receiver. Practically, this technique amounts to electronically scanning the acting element over the array. This technique leads to N A-scans;

c) sparse matrix capture: this term refers to the possibility to select in a deterministic or random way a subset of active transmitters and/or receivers giving a subset of the FMC data.

B.3.3 Application of delay laws

Delay laws may be applied in order to form beams during transmission as follows:

a) plane wave imaging (PWI): this technique consists in transmitting plane waves at n different angles by applying adequate delays to the transmitters on the array. The signals are collected on the N elements of the array, leading to $n * N$ signals to be processed (typically $n < N$);

b) virtual sources: this technique aims at creating “virtual sources” in the part transmitting higher energy than the individual elements of the array. The objective is to enhance S/N in case of noisy materials. The acquisition consists of dividing the array into active sub-apertures on which delay laws are applied in order to focus ultrasound at selected points close to the array, which then act as virtual sources. Every sub-aperture is associated with one virtual source. The set of virtual sources behaves as a virtual array. The number of signals is $n*N$, where n is the number of sub-apertures on the array.

B.3.4 Application of coded excitation to the array

This technique consists in firing successive shots with the whole array but with a selection of active elements driven by a numerical code. This technique aims at increasing S/N in attenuative materials.

B.4 Reconstruction of multiple imaging paths

Discontinuities can be detected by different mechanisms along different imaging paths (including tip diffraction, reflection, corner echoes and mode conversion).

The implementation of TFM for multiple imaging paths consist of:

a) selection of several imaging paths;

b) computation of an image for each imaging path, by applying a computation step and a summation step as described in B.2.2.

The result of this processing may be displayed as one image incorporating images of several paths or as separate images corresponding to selected imaging paths.

B.5 Adaptive TFM

In some cases, the times of flight, *tij*(P), is not known exactly, for example due to the imaging path containing an interface whose position is not exactly known. A typical example is the shape of a weld cap, which is irregular. In the adaptive TFM (ATFM) algorithm, in a first step, a measurement is made of the position of the interface based on the information in the FMC data. The times of flight *tij*(P) are subsequently adjusted based on this information, and a TFM image is made based on the adjusted time of flight.

Similar processes may be repeated in multiple steps, for additional unknown properties in the ROI.

Annex C
(informative)

Checking of the FMC/TFM setup, ROI and grid

C.1 Overview

C.1.1 General

This annex gives guidance on checking the FMC/TFM setup, ROI and grid. Due to FMC/TFM being an imaging method consisting of a data acquisition and an imaging step, which both involve sampling, special care needs to be taken for the grid point spacing. Coverage and resolution are implicitly tested with the procedure described below as well. Sensitivity can also be checked, as the procedure is performed in the same arrangement as the amplitude correction procedure described in 10.3.

In the practical implementation of the basic TFM algorithm, each point in the image is reconstructed by shifting A-scans in time base in the full matrix of data and adding the values of the A-scans for the grid point position. Since the A-scan consists of ultrasonic unrectified and unfiltered signals, received signals have a cyclic nature with the frequency of the ultrasound. If the grid point density of the image is insufficient, it is possible that successive A-scans have an opposite phase and cancel each other out. The amplitude of a small reflector thus increases and decreases on small changes to the probe position if the grid is chosen too coarse.

C.1.2 Image resolution

In common language, when discussing imaging, resolution can mean two things:

a) the amount or density of grid points in a display or image;

b) the ability to resolve closely spaced objects independently.

In this document, both are discussed. Item a) is addressed by the terms grid count and grid point spacing, while item b) is addressed by the term resolution.

When an application requires a specified resolving power, the test procedure should indicate the approach to verify this. The test procedure can for example rely on reference blocks containing a series of pairs of side drilled holes (SDHs) of different diameters separated by a distance equal to their diameters.

C.1.3 Resolution and ROI grid spacing

The required grid point spacing is determined by the following factors:

a) resolution required for the testing;

b) overall area to be covered;

c) processing power/required speed;

d) grid point spacing required to obtain an image with a stable amplitude.

Typically, FMC/TFM is used either for the imaging capability or for enhanced sizing capability. Depending on what is required, the grid may be set up coarser or finer. However, the amplitude stability has a relationship with the wavelength and in a grid set too coarse small reflectors can be missed or undersized.

For basic FMC/TFM, a stable amplitude is achieved when the grid point spacing is smaller than one fifth of the wavelength ($\lambda/5$). Since the amplitude stability is impacted by many factors (e.g. probe characteristics) and since other implementations exist for which this rule does not hold, a procedure is described here that allows for checking of amplitude stability over the ROI.

C.2 Amplitude stability verification procedure

C.2.1 Equipment and tools

This procedure is intended for use with FMC/TFM equipment running the same software release that will be used during the testing.

The procedure should be performed with:

a) probe and wedge of the same manufacturer and model as the one used in the testing;

b) test block or a reference block with a vertical row of SDHs (e.g. ISO 19675);

c) optionally a clamp, e.g. a ratchet bar clamp, to keep the probe in place on the block.

The direction in which the ROI is be moved during this test depends on the setup:

— if the ROI is mainly below the array (top scanning as defined in ISO 23864), then the ROI shall be moved in vertical direction;

— if the ROI is mainly besides the array (side scanning as defined in ISO 23864), then the ROI shall be moved in horizontal direction.

Alternatively, for side scanning, a micro adjuster can be used to move the probe on the block instead of changing the offset of the ROI.

C.2.2 Verification setup

The equipment shall be set up with the ROI settings identical to that used for the intended testing. During the verification test, only the ROI offset shall be changed.

The equipment shall be set up on the vertical row of SDHs and fixed with the array clamped on three different positions of the row of SDHs:

a) in the middle of the ROI;

b) approximately 2 mm from the left edge of the ROI;

c) approximately 2 mm from the right edge of the ROI.

The SDH with the highest amplitude shall be set to 80 % screen height.

C.2.3 Verification process

The offset is incremented by a specified amount. The increment amount is calculated using Formula (C.1):

$$i = \lambda / 20 \quad \text{(C.1)}$$

where

i is the increment amount;

λ is the wavelength.

Table C.1 provides an example for ferritic carbon steel.

Table C.1 — Example of increment amounts (rounded) for several probe frequencies

Probe frequency	λ		i	
	L	T	L	T
MHz	mm	mm	mm	mm
1	5,9	3,2	0,30	0,16
2,25	2,6	1,4	0,13	0,07
5	1,2	0,6	0,06	0,03
7,5	0,7	0,4	0,04	0,02
10	0,6	0,3	0,03	0,02
NOTE L means longitudinal waves, T means transverse waves.				

The verification process can be applied on real-time displayed TFM images or by post-processing stored FMC data. The following steps should be followed in order.

— Step 1: Record the maximum amplitude of each of the SDHs in the ROI, in percentage of full-screen height (FSH), in a table.

— Step 2: Increment the offset by the increment amount.

— Step 3: Compute TFM settings for this offset.

— Step 4: Display the TFM image for this offset. Return to Step 1 until 20 increments have been performed.

This process shall be performed for each of the three probe positions mentioned in C.2.2.

C.2.4 Result calculation

For each SDH for each probe position in the result table the highest (β_H) and the lowest value (β_L) shall be determined as a percentage of FSH. The amplitude stability (β) for each SDH, at each probe position is calculated using Formula (C.2):

$$\beta = 20.\log\left(\frac{\beta_H}{\beta_L}\right) \tag{C.2}$$

where

β is the amplitude stability in dB;

β_H is the highest amplitude value as a percentage of FSH;

β_L is the lowest amplitude value as a percentage of FSH.

The verification has been successfully passed if the amplitude stability values for each SDH at each probe position are:

— maximum 2dB (i.e. ±1 dB) if the absolute value of the signal amplitude is to be used for sizing;

— maximum 4dB (i.e. ±2 dB) if a type of sizing is used that does not rely on the absolute amplitude of the signal amplitude.

If the amplitude stability is over the specified value above, the grid point spacing shall be decreased.

C.2.5 Reporting

The report should contain the three tables produced in the verification process, the amplitude stability value and the following information:

a) ROI parameters (e.g. a screen shot of the TFM settings window);

b) calculation of the increment amount;

c) three tables with SDH amplitudes and amplitude stability values;

d) settings and equipment used in the testing:

- probe(s);
- wedge(s);
- instrument;
- test block(s);
- software release;
- gain (measurement, interpretation);
- gain correction settings if applicable.

Annex D
(informative)

Recommended settings and examples of FMC/TFM images

D.1 Overview

This annex provides information on how FMC/TFM can be used for detection, characterization and sizing of a number of damage types commonly found in industry. The information in this annex should aid in development of specific procedures using FMC/TFM and the settings presented in this annex are indicative only – specific applications require settings to be selected and verified appropriately.

Note also that other ultrasonic techniques (and other testing methods) can also be used to inspect for these damage types.

D.2 Application on HTHA or similar damages

D.2.1 General – various type of hydrogen damages

D.2.1.1 High-temperature hydrogen attack (HTHA)

HTHA can be defined as a cracking process due to hydrogen permeation through the steel and reaction with carbides, leading to micro-cracks. Damage propagates from the surface exposed to hydrogen. Imperfections can be located in the parent metal or in the weld. The main limitation for detection is that the cracks need to have sufficiently large individual sizes to interact with ultrasonic beams, regardless of their orientations.

D.2.1.2 Other hydrogen induced damages

Carbon and low alloy steels can be affected by different forms of cracking mechanisms when they are exposed to acidic aqueous media containing hydrogen sulphide.

In wet H_2S environments, an electrochemical reaction can occur on the surface of pressure vessel walls, leading to the absorption of hydrogen atoms by the steel.

The diffusion of hydrogen atoms through the metal can have several effects:

a) formation of molecular hydrogen H_2 in local areas;

b) decrease in the toughness of the metal;

c) weakening of the metallic bonds.

The combination of these effects can result in different types of failure mechanisms[11]:

a) hydrogen induced cracking (HIC). Stepwise cracking (SWC) and blistering are two specific forms of HIC;

b) sulphide stress cracking (SSC);

c) stress-oriented hydrogen-induced cracking (SOHIC).

The specific settings described in D.1 used for HTHA may also be applied for detection of HIC in combination with PAUT beam forming focused scans in order to confirm stepwise cracking.

The specific settings described in D.4 used for stress corrosion cracking (SCC) may also be applied for detection of SOHIC.

D.2.2 Specific settings

The FMC/TFM technique can be used as a complementary approach to other non-destructive methods for the detection of HTHA damage. Such other methods and techniques are described in API RP 941, which include time-of-flight diffraction (TOFD), backscattering and velocity ratio.

Surface roughness should not exceed 6,5 µm and the geometry should present no waviness of the surface producing a gap larger than 0,5 mm.

As specified in Clause 10, checking, settings and items to take into account are at a minimum those required for conventional PAUT beam forming testing (see ISO 13588).

With respect to the detection of HTHA damage, the following settings should be applied.

a) For setting the sensitivity, a reference reflector should be used. It can be either the top of a notch with a width of 0,2 mm or a side drilled hole (SDH) located at a depth corresponding to the component thickness with a tolerance of ±20 %. A signal-to-noise ratio of at least 12 dB should be observed. When SDHs are used, the examination sensitivity should be increased to ensure the detection of diffraction signals;

b) The amplitude of the reference reflector should be set to between 80 % and 100 % of full screen height (FSH);

c) A sensitivity correction should be carried out on reflectors located at various depths. Figure D.1 shows the results obtained on the 3 SDHs implemented in the ISO 19675 calibration block;

d) The evaluation is based on any TFM indications that exhibit specific patterns and are detected above the background noise.

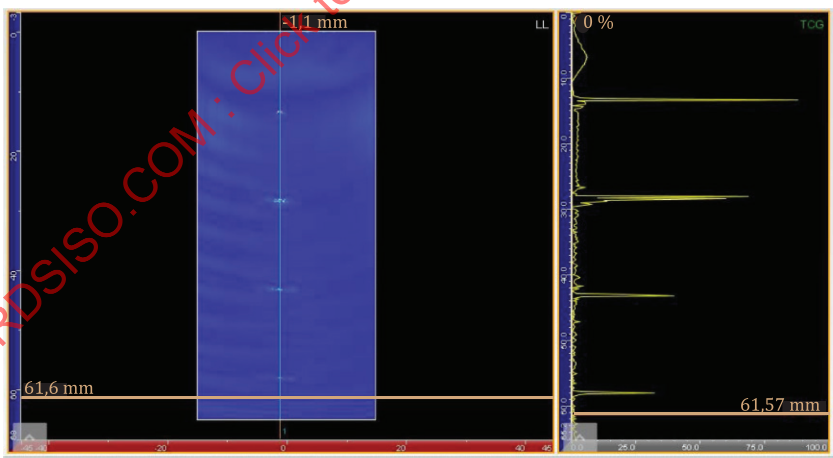


Figure D.1 — Sensitivity correction (Frequency 15 MHz – LL imaging path)

D.2.3 Probes

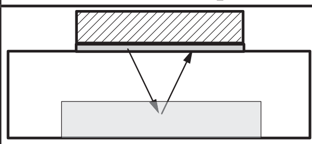
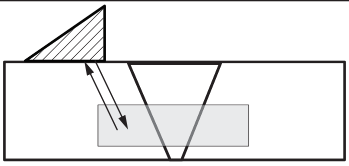
In order to get the best signal-to-noise ratio resulting from interaction between the sound beam and HTHA damage, the probe frequency should be between 7 MHz and 15 MHz for compression waves or between 3,5 MHz and 7,5 MHz for shear waves. The array probes can be either linear or matrix.

The active aperture is to be set as large as possible. The main limitation can be the component contact surface (curvature, clearance). A minimum of 32 active elements is required.

D.2.4 Recommended imaging paths

The recommended FMC/TFM imaging paths to use are given in Table D.1.

Table D.1 — Recommended imaging paths for HTHA damage

HTHA damage	With side scanning	With top scanning
Testing of base material	Top scanning is preferred.	 Direct imaging path recommended (LL). Direct contact or 0° wedge.
Welds: testing of heat affected zone	 LL or TT imaging path recommended.	Side scanning is preferred.
NOTE The same imaging path and settings can be used in parent metal for HIC/SWC examinations.		

D.2.5 Typical images

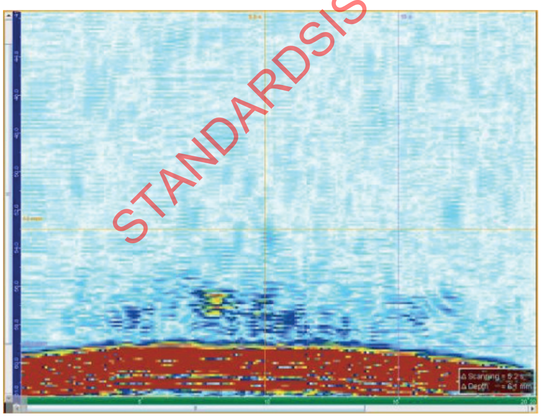
D.2.5.1 HTHA images

Typical FMC/TFM images obtained on HTHA damages are provided in the following figures:

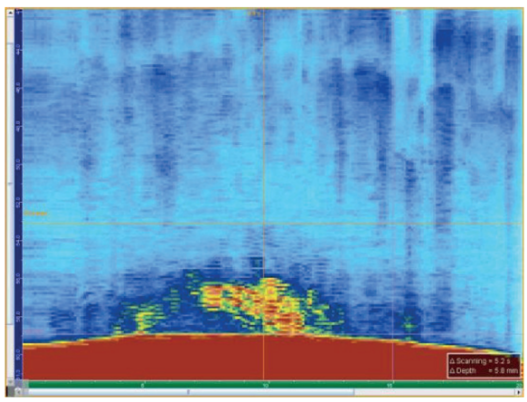
— Figure D.2 a) shows a single FMC/TFM image on a damaged steel block having a thickness of 60 mm. The probe frequency is 7,5 MHz. The LL imaging path was used;

— Figure D.2 b) shows a volumetric merged view of multiple images.

Merged views generally allow obtaining better results.



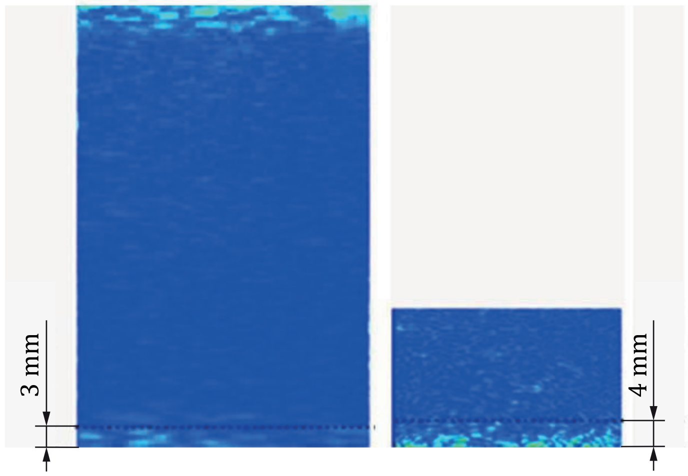
a) Single FMC/TFM image



b) Volumetric merged view

Figure D.2 — FMC/TFM images on HTHA damage

Figure D.3 illustrates the benefits of FMC/TFM to improve the capacity of the operator to discriminate HTHA patterns from other kinds of damage.



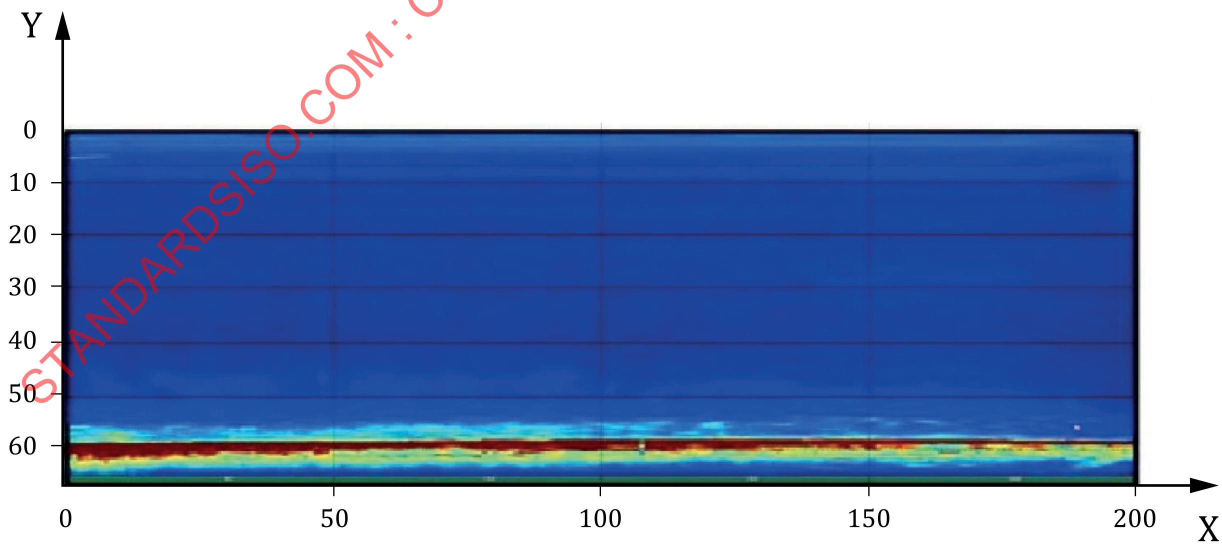
a) By linear PA normal beam

b) By FMC/TFM

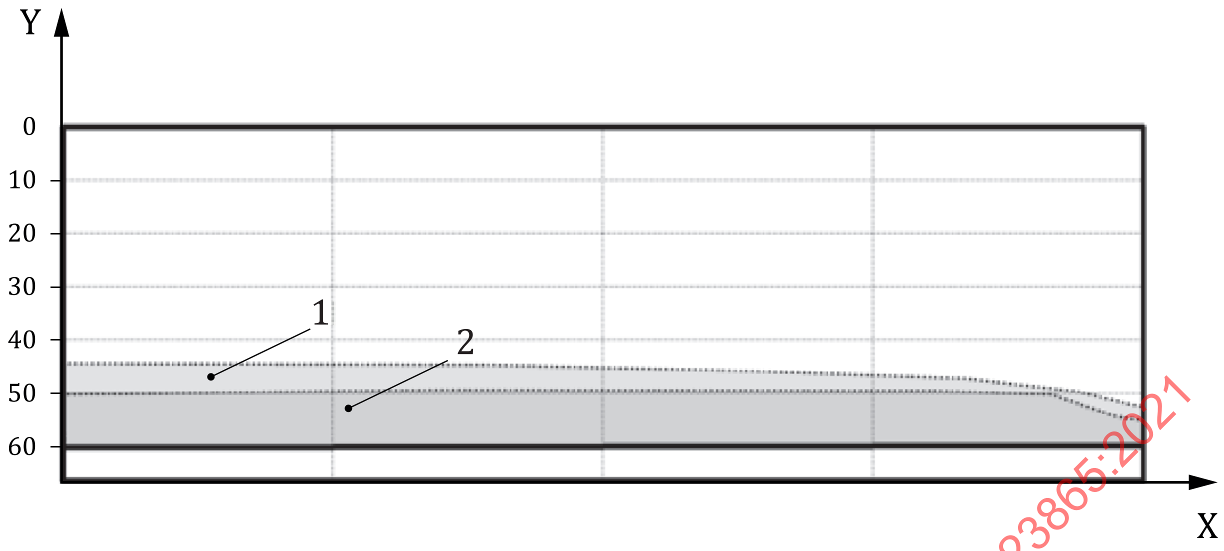
Figure D.3 — Comparison of PAUT and FMC/TFM on early HTHA damage

Identification of TFM indications may be based on recognition of specific patterns applied to post processed images, such as cumulative side views, merged views, specific colour palettes or filters. These specific patterns should have been previously defined on representative qualification blocks with known HTHA damages. Simulation tools may be used for generating these patterns. Typical patterns are related and associated to density and spatial distribution of TFM indications, spatial distribution of TFM indication's amplitude versus depth, change of structural noise, identification of "pockets", "clouds", etc. Example of typical patterns and associated micrographs are given in Reference [12].

Figure D.4 shows an example of such identification based on changes of FMC/TFM image pattern or texture. Operators trained to recognize specific patterns are also able to discriminate between early and moderate damages on such images.



a) FMC/TFM image – merged view



b) Interpretation of the damaged areas related to the FMC/TFM image

Key

1 early damage

2 moderate damage

Figure D.4 — Detection of early and moderate HTHA damage

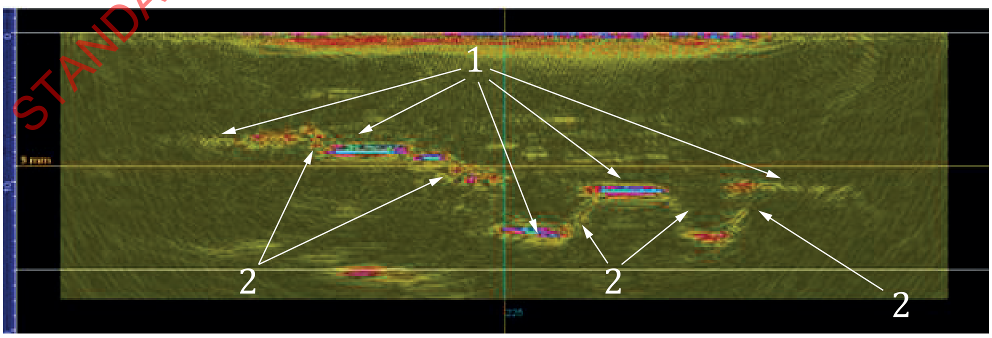
Detection of HTHA at early stages remains difficult especially on dirty steels having a lot of inclusions and can require the use of complementary techniques.

Because there are no ultrasonic acceptance levels dedicated for HTHA, metallurgical expertise is generally required to provide the interpretation of the TFM indications detected by FMC/TFM testing.

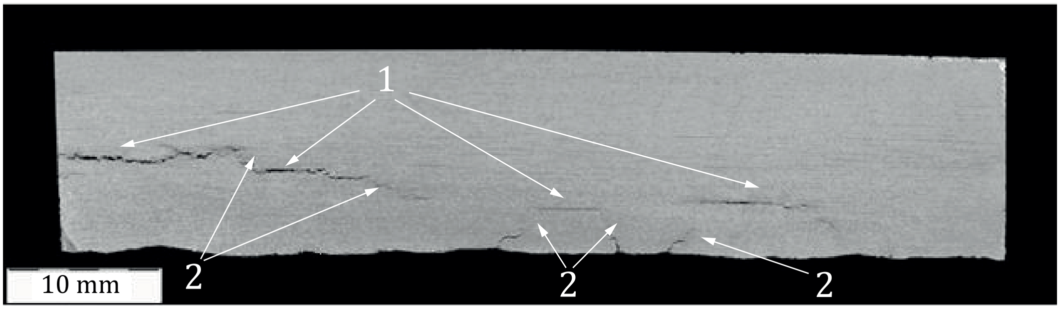
D.2.5.2 HIC/step wise cracking images

Figure D.5 a) is obtained with similar settings as those used for HTHA testing. It shows the detection of HIC and SWC in a carbon steel plate sample (actual thickness is 13 mm) by top scanning with direct imaging path (LL).

Figure D.5 b) shows the macro-section of the test object at FMC/TFM image location. Horizontal cracks (HIC) as well as stepwise cracks (SWC) are highlighted.



a) FMC/TFM image



b) Macro section corresponding to the FMC/TFM image

Key

1 HIC

2 SWC

Figure D.5 — Detection of HIC/SWC cracking

D.3 Corrosion testing

D.3.1 Various types of corrosion damages

Corrosion refers to the processes of physiochemical interactions occurring between a metal and its environment leading to a degradation of the function of the metal.

The following types of corrosion in steel vessels and piping components are to be considered, in accordance with their location and shape, when selecting the imaging paths to be applied:

a) uniform corrosion;

b) pitting;

c) erosion;

d) deposit attack;

e) crevice corrosion;

f) galvanic corrosion;

g) flow induced corrosion;

h) flow accelerated corrosion;

i) weld zone corrosion;

j) combinations of two or more of the above types of corrosion.

Imperfections to detect can be surface breaking or connected to the opposite scanning surface. Internal corrosion can be located in parent metal or affect the weld root.

D.3.2 Specific settings

Corrosion mechanisms produce different shapes, location and type of reflecting surfaces. Specific recommendation regarding the settings to be applied for each case cannot be given, as it would depend on the access conditions, material thicknesses and other parameters.

The FMC/TFM technique can be used as an alternative or a complementary approach to other non-destructive techniques for the detection and assessment of corrosion damage. Such other techniques are described in ISO 16809 and EN 17290. PAUT is also increasingly being used to perform corrosion mapping where the E-scan is used. The probe is mechanically moved perpendicularly to the electronic scanning direction and a C-scan is produced allowing a high testing rate.

Before applying FMC/TFM for corrosion assessment, it is essential to have knowledge of the type(s) of material loss to be expected, and to design a test procedure adapted to the specific type of wear, corrosion or erosion likely to occur, taking into account the location of the corrosion and it shape.

It is recommended to verify the test procedure on test blocks having representative reflectors (location, shape, size, etc.) of the damage likely to occur and a thickness range covering the expected range of the test object. Material and temperature should be equivalent to the test object.

D.3.3 Probes

Probe selection depends on the test object geometry, material thickness, surface condition and coating condition.

When the test object is curved, consideration should be given to the selection of probe size.

Frequency and aperture should be selected in accordance with the test object geometry, thickness and type of corrosion to detect.

D.3.4 Recommended imaging paths

The recommended FMC/TFM imaging paths to use in accordance with the corrosion location are given in Table D.2.

Table D.2 — Imaging paths for detection of corrosion

Corrosion	**With side scanning**	**With top scanning**	
	internal surface imperfection	internal surface imperfection	surface breaking imperfection
Testing of base material	LL or TT	Direct imaging path recommended (LL). Direct contact or 0° wedge.	Direct imaging path recommended (LL). Direct contact or 0° wedge.
Corrosion in weld	LL or TT imaging path recommended. Wedge angle should not exceed 30°.	Direct imaging path recommended[a]	LL-LL or TT-TT imaging path recommended[a]

[a] The use of this imaging path is limited to very specific cases when good surface conditions are met, allowing use of the ATFM technique.

D.3.5 Typical images

Figure D.6 shows an FMC/TFM image obtained on a shallow wide corrosion. The main advantage to apply FMC/TFM technique in that situation is in determining the corrosion profile in its whole extent. The connected angle values with the back wall of the test object can be determined accurately.

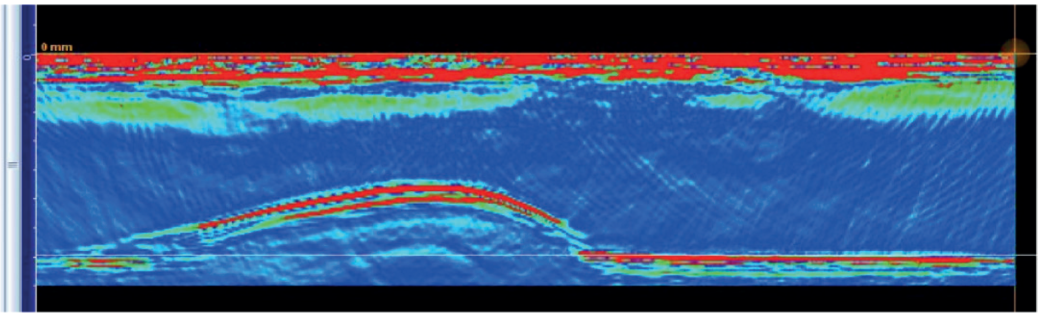


Figure D.6 — FMC/TFM image on a shallow wide internal corrosion

D.4 SCC testing

D.4.1 General

Stress corrosion cracking (SCC) is by nature an in-service degradation mechanism that takes place over time and in specific service conditions (materials, fluid content, temperature, loads). However, once initiated, it can rapidly lead to catastrophic failure, as evidenced throughout industry in many common engineering materials, including carbon steel, stainless steels and duplex steels. Hence, the ability to detect the multifaceted profile of SCC damage, possibly as small as 1 mm in through-wall height, to be able to characterize its morphology and to accurately size the through-wall extent is critical for analysing the threat to integrity of the component while in service.

Examples of different size cracking in stainless steel cladding are given below.

a) SCC in cladding applied metallurgically is shown in Figure D.7. Measured through-wall sizes are as follows: 0,12 mm (left), 0,45 mm (middle) and 3,13 mm (right);

b) SCC in cladding applied by weld overlay to carbon steel pipe work to protect it from corrosion is shown in Figure D.8. Measured through-wall size is approximately 1 mm. The microstructure has been etched to reveal the austenitic structure.

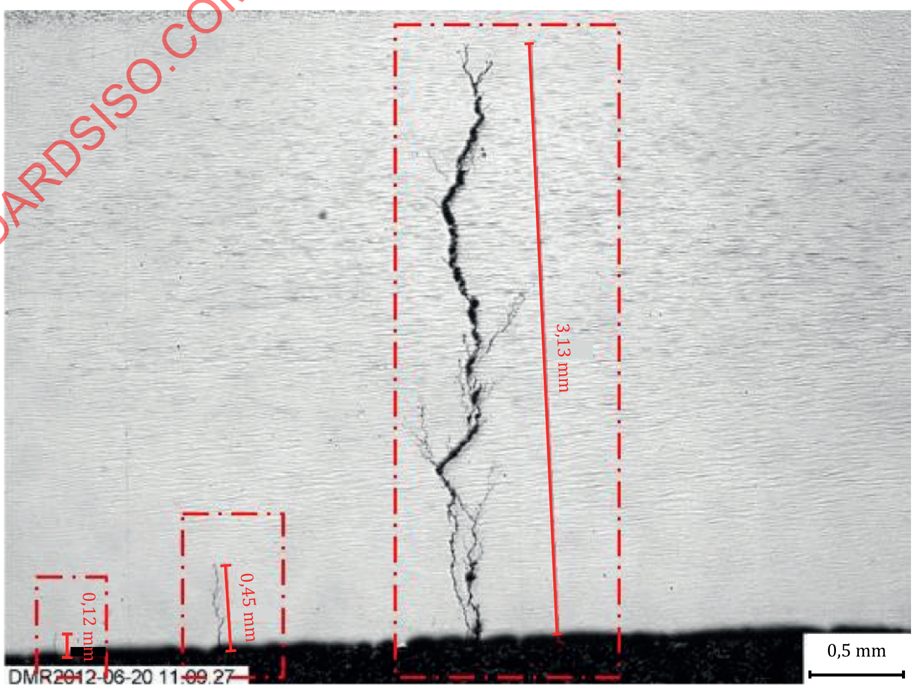


Figure D.7 — SCC damage in metallurgically applied austenitic cladding

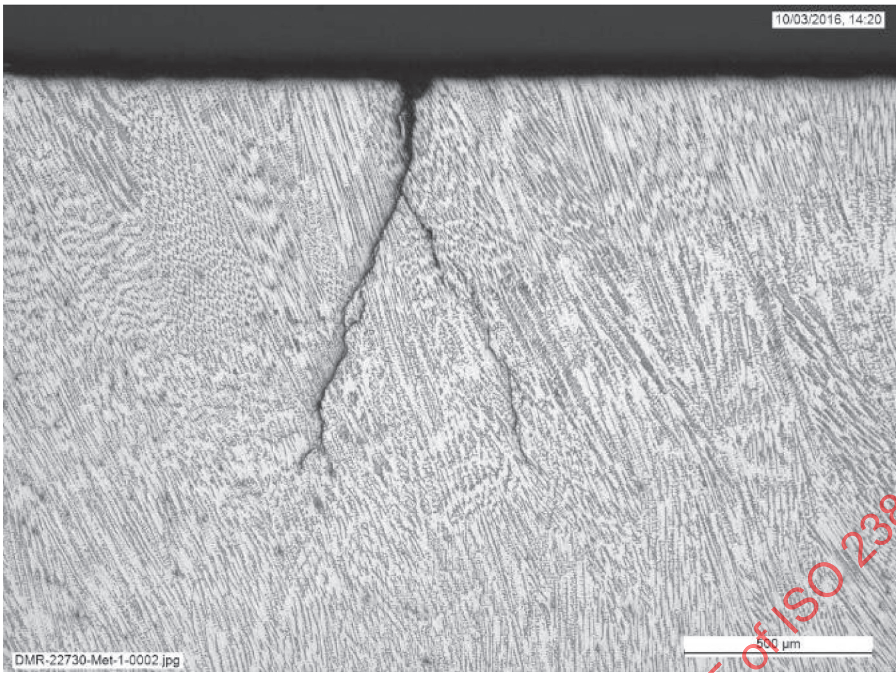


Figure D.8 — Micrographs of a SCC in stainless steel weld overlay cladding

D.4.2 Specific settings

D.4.2.1 Scanning surfaces and geometry

The scanning surface roughness should not exceed 6,5 µm.

D.4.2.2 Calibration

The ROI should be set over the part of the component where SCC is likely to occur. Nominally, this is a surface exposed to corrosive fluids and the cracking that develops is open to the surface.

D.4.2.3 Reference levels

Ideally, exemplar damage in a representative component should be used as a reference. This leads to the best possible outcomes during testing. The use of reference specimens with either artificial targets (such as EDM notches) or actual damage is particularly mandated when SCC takes place in an anisotropic, heterogeneous material, such as weld overlay cladding.

D.4.2.4 Sensitivity

The detection of SCC is nominally through the corner-trap effect, which is represented by the LL-L or TT-T imaging paths presented in Table D.3. For the purposes of detection in isotropic or homogeneous materials, sensitivity can be set to 6 dB greater than the corner from a reference notch or crack. Acceptance levels need to be determined by project criteria. If sizing by detection of diffracted signals from the cracks is sought, then sensitivity should be set to at least 14 dB greater than the corner from a reference notch or crack. Optimization of the sensitivity level for diffraction-based sizing is likely required using reference specimens or using limited destructive validation during the testing campaign.

D.4.3 Probes

SCC can be small and can need to be detected while it is less than 1 mm in through-wall size, depending on a structural integrity analysis. Arrays with a frequency of 10 MHz with a minimum of 32 elements are recommended. In general, the frequency shall be increased as far as possible but this depends

