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Non-destructive testing — Radiation methods for computed tomography —

Part 3: Operation and interpretation

Essais non destructifs — Méthodes par rayonnements pour la tomographie informatisée —

Partie 3: Fonctionnement et interprétation

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document 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).

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This second edition cancels and replaces the first edition (ISO 15708-3:2017), which has been technically revised.

The main changes are as follows:

— correction of Figure 5;

— correction and reordering of content in Clause 5;

— correction of definitions for N_C and N_A in Formula A.1;

— correction of definition for σ in Formula A.2;

— editorial changes.

A list of all parts in the ISO 15708 series can be found on the ISO website.

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Non-destructive testing — Radiation methods for computed tomography —

Part 3: Operation and interpretation

1 Scope

This document provides an overview of the operation of a computed tomography (CT) system. This document specifies steps for interpretation of CT results with the aim of providing the operator with technical information to enable selection of suitable parameters.

This document is applicable to industrial imaging (i.e. non-medical applications) and specifies a consistent set of definitions of CT performance parameters, including how these performance parameters relate to CT system specifications.

This document is applicable to computed axial tomography.

This document does not apply to other types of tomography such as translational tomography and tomosynthesis.

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 15708-1, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Vocabulary*

ISO 15708-2:2025, *Non-destructive testing — Radiation methods for computed tomography — Part 2: Principle, equipment and samples*

ISO 15708-4:2025, *Non-destructive testing — Radiation methods for computed tomography — Part 4: Qualification*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15708-1 apply.

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

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

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

4 Operational procedure

4.1 General

For target-oriented computer tomography (CT) non-destructive testing inspection procedures, the test and measurement tasks are defined in advance with regard to the size and type of features/defects to be verified, e.g. by specifying appropriate acceptance levels and geometry deviations. In the following, the process steps of a CT application are described and information on its implementation is provided.

4.2 CT system set-up

4.2.1 General

The set-up of the CT system is based on the requirements for the respective task. The required spatial resolution (taking into account the tube focal spot size), the contrast resolution, the voxel size and the CT image quality can be derived from these requirements. The quality of the CT image is determined by different parameters, which, under certain circumstances, counteract each other.

In the following, system parameters are described and information on setting up a CT system for non-destructive testing inspection is provided. Due to the interactions between various system parameters, it can be necessary to run through the set-up steps several times to acquire optimal data.

The optimum energy is the one that gives the best signal-to-noise ratio and not necessarily the one that gives the clearest radiograph (the dependence of the detector efficiency on the energy shall be taken into account). However, in order to differentiate between materials of different chemical composition, it can be necessary to adjust the accelerating voltage to maximise the difference in their linear attenuation coefficients.

4.2.2 Geometry

The source-detector and source-object distances and thus also the beam angle used should be specified. To achieve high spatial resolutions, the projection of the object onto the detector is magnified. The magnification is equal to the ratio of the source-detector distance to the source-object distance. An increasing source-detector distance leads to a reduced radiation intensity at the detector and therefore to a reduced signal to noise ratio. Accordingly, this also applies when using detectors with improved detector resolution, which results in a reduction of the signal-to-noise ratio due to the reduced radiation dose per pixel. For this reason, it is generally preferable to minimise the source-object distance.

To obtain high radiation intensity at the detector, the source-detector distance should be selected as small as possible taking into account the required spatial resolution, so that the beam cone still fully illuminates the detector. In the case of 3D-CT, the (in general vertical) total cone beam angle measured parallel to the rotation axis should typically be less than 11° in order to minimise such reconstruction-determined distortions of the 3D model ("Feldkamp" algorithm [2]). In addition, these restrictions do not apply for the perpendicular (in general horizontal) beam angle. At a higher geometric magnification, the object shall be positioned as near as possible to the source, taking into consideration the limit of sharpness due to the size of the focal spot of the X-ray source. The object shall be rotated by at least 180° plus the beam angle of the X-ray beam, whereby the data quality is improved by an increased rotational angle. For this reason, the object is typically rotated by 360°. Ideally, the number of angular increments should be at least $\pi/2$ × matrix size (odd number of projections per 360°), where the matrix size is the number of voxels across the sample diameter or its largest dimension. For more information, see 5.5.

The number of projections should be > (π × matrix size) for best reconstruction quality (number of projections per 360°).

In order to obtain information about the specimen that is as complete as possible, the object (or the interesting section of the object) shall be completely mapped on the detector in each projection. For large components that exceed the beam cone, a so-called measurement range extension is used. This extension of the measuring range is achieved by laterally displacing either the object or the detector, recording the projection data in sequential measurements, and finally, concatenating (joining) them. Under certain circumstances, it is also possible to scan only a part of the object (region-of-interest CT), which leads to limited data quality in the form of so-called truncations.

A possible deviation of the recording geometry (offset between the projected axis of rotation and the centre line of the projection image) shall be corrected to obtain the most accurate reconstruction as possible. This shall be achieved by carefully aligning the system or by software correction.

4.2.3 X-ray source

At the X-ray source, the maximum beam energy and the tube current shall be set such that sufficient penetration of the test object and the maximum tube power with a sufficiently small focal spot are ensured. The required voltage shall be determined by the maximum path length in the material to be X-rayed in accordance with ISO 15708-2:2025, 8.2. For optimum *conditions* of the measurement results, an attenuation ratio of less or equal to 1:10 should be used. This means, that the grey value after the sample should be about 10 % of the free beam value. The optimal range can be achieved by using pre-filters at the tube port. It should be noted that each pre-filter reduces the intensity. Pre-filters have the additional advantage of beam hardening, which reduces the beam hardening artifacts after reconstruction, although further improvements can be made through software corrections.

4.2.4 Detector

The following detector settings need to be set appropriately for the sample to be scanned:

— exposure time (frame rate);

— number of integrations/averagings per projection;

— digitisation, gain and offset;

— Skip projections

— binning.

If necessary, corrections for offset, gain and bad pixels (which may depend on X-ray settings) should be applied.

The individual CT projection is determined by the geometric resolution, the sensitivity, the dynamics and the noise of the detector. The gain and exposure time can be adjusted together depending on the radiation intensity of the source so that the maximum digitised intensity in the free beam does not exceed 90 % of the saturation level.

To reduce scattered radiation, a thin filter, grid, or lamellae can be used directly in front of the detector (intermediate filtering).

The ideal acquisition time is dependent on the required quality of the CT data and is often limited by the time available for testing.

4.3 Reconstruction parameters

The volumetric region to be reconstructed, the size of the CT volume (in terms of voxels) and its dynamic range (which should take into account the dynamic range of the detector) shall be specified. To achieve sufficient CT image quality, the settings for the reconstruction algorithm or corrections should be optimised.

The volumetric region is defined by the number of voxels along the X, Y and Z axes.

4.4 Visualization

Using volume visualisation, the reconstructed CT data image can be presented as a 3D object. Individual grey values can be assigned any colour and opacity values to highlight or hide materials with different X-ray densities. Zooming, scrolling, setting contrast, brightness, colour and lighting facilitate an optimal presentation of the CT volume. In addition, it is possible to place user-defined sectional planes through the object to examine the internal structure, or to visualise the CT volume interactively, for example by rotating and moving it as a 3D object. Image processing can be applied to CT data to improve feature detection.

There is a possibility that the whole CT volume cannot be loaded at full resolution into memory at once. Consequently, the CT volume can be split into different smaller parts of the total volume for separate viewing.

4.5 Analysis and interpretation of CT data

4.5.1 General

Typical internal features for inspection are pores, cavities, cracks, inclusions, impurities or inhomogeneous material distributions.

Typical measurement tasks are obtaining dimensional properties (such as length or wall thickness) or calculating object morphology.

4.5.2 Feature testing/defect testing

Features in the sample generally lead to changes in the CT grey value in the CT data. The analysis of CT data is performed by qualified personnel using software. A suitable contrast range or an automatic or manual calibration is used. The location, the CT grey value and the dimensions of features can be determined. Several tools are available for this purpose, including manual or automatic tools such as strobe lines or gauges that engage at grey value thresholds or edges. To examine the structure and location of assembled components, a qualitative comparison of CT volumes without determination of the dimensions can be sufficient.

For automatic determination using visualisation software tools (e.g. for defect analysis), a calibration via specification of a grey value range is, in general, required for the sample material to be measured. The grey values can be specified manually using histograms or in an interactive manner.

The detectability of features depends on the size of the feature relative to the geometric resolution and the contrast resolution compared with the contrast difference of the feature to the base material, as well as the quality of the image (signal to noise ratio, etc.) and any possible interference effects between adjacent voxels (partial volume effect). For the detectability of singular pores, cavities or cracks, their minimum extent should typically be 2 to 3 times the demagnified pixel size of the detector (at the position of the sample).

4.5.3 Dimensional testing

4.5.3.1 General

Depending on the task at hand, various methods are currently used to determine geometric features. Point-to-point distances can be determined manually in the CT slices, or more complex features can be extracted with the help of analysis software.

The measurement of the geometric properties of an object using CT is an indirect method, in which the dimensional measurement takes place in or is derived from CT data. For this reason, in order to facilitate precise measurements, an accurate knowledge of two important variables is necessary:

— the precise image scale or voxel size;

— the boundary surface of two materials, for example the component surface (material-to-air transition), which can be determined via a CT grey value threshold in the CT volume.

4.5.3.2 Determination of precise image scale

The precise image scale or voxel size shall be determined by measuring a suitable calibration standard (together with the measurement object and directly before/after testing of the object inspection) or by using a reference geometry on the object. For this purpose, the voxel size or magnification M, specified by the CT system is compared with the actual available and precisely determined (using the reference body/geometry) voxel size or magnification. Thus, for example, the exact voxel size can be determined with high precision via measurements without the disturbing influence of other variables, e.g. the precise position of the component surface (grey value threshold) in the CT volume, for the centre distances of a test piece (e.g. dumbbell, see Figure 1). In this procedure the CT grey values of the test item can be influenced by the accompanying reference bodies (e.g. due to changes in the contrast ratios, interferences and artefacts). Based on the actual voxel sizes determined in this way, the visualisation software can be scaled/corrected accordingly to the voxel size specified by the system.

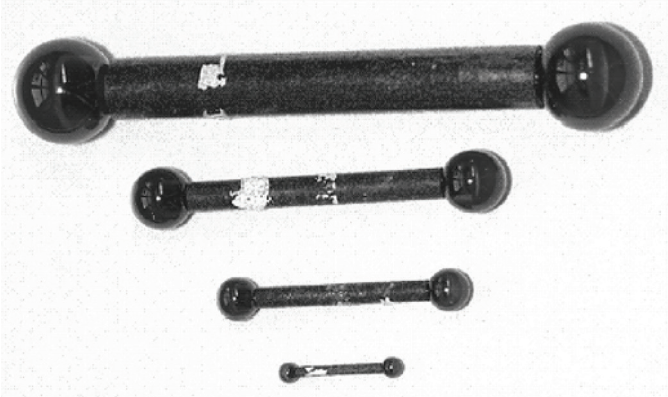

Figure 1 — Reference objects (dumbbells of different sizes)

4.5.3.3 Threshold value determination

For dimensional measurements, the component surface or material contact surface shall be determined in the CT volume. The component surface usually results from the transition from solid object to surrounding air. The boundary surface is defined via a threshold value and is thus dependent on the materials and the X-ray settings. This threshold can be specified globally for the entire CT volume as an average grey value of e.g. the material and air. This is sometimes known as the "ISO50 threshold" (from the Greek, "isos" means "equal"). A global threshold value or calibration using the ISO50 threshold is suitable for many measurement tasks on objects made from homogeneous materials.

A global threshold is not suitable for objects made of different materials. In these cases, different thresholds shall be used according to the materials either side of the boundary. Even with objects made from homogeneous materials, beam hardening, scattering and other artefacts can result in local dimming or lightening in the CT volume, which would distort the measurement results. The grey value threshold, e.g. for surfaces inside the component, therefore often differs from that for surfaces on the outside of the component. If necessary, the threshold can be determined locally from the grey levels on both sides of the boundary. A determination of the overall component surface via locally determined threshold values is more tolerant towards contrast variations and artefact influences, but more time consuming.

4.5.3.4 Adjustment of geometrically primitive bodies

In addition to simple point-to-point operations (see 4.5.3), methods from coordinate measurement technology, such as reference geometry adjustment can also be used. Here, so-called geometric primitive bodies or reference elements (e.g. planes, cylinders, spheres, etc.) are fitted, using software, to object contours of interest in the correspondingly calibrated data. At the reference elements, geometric features (e.g. diameter, distances, angles, etc.) are determined directly or by combining reference elements. Due to the statistic averaging and the reduction of the user influence, the fitting of these elements to the typically several thousand measurement points of the corresponding data, often results in significantly higher precision than via the manual distance measurement of two points.

4.5.3.5 Generation of geometric data

So-called triangular models can be extracted from the voxels and calibrated grey value threshold. These models represent the calibrated threshold value ISO50-surface, i.e. the material surface in the form of linked triangles. The triangular model contains – as part of the extraction process precision (see below) – the geometry information on the object surface. It consists of only two types of information: the so-called vertices and the information about which vertices belong to a triangle. The vertices are 3D points that lie on the threshold value ISO50-surface. The quantity of all vertices is also designated to as a point cloud. It is initially the linking information, i.e. the information about which three vertices from a triangle that defines the course of the object surface.

A standard format for data exchange is the so-called STL file format (ASCII or binary and dimensionless). Alternatively, the point cloud (vertices without triangle information) can be exported, whereby important information on adjacent vertices is usually lost and, if necessary, should be reproduced subsequently.

The geometric quality of the generated point cloud or triangular model depends entirely on the number and position of the vertices. Since only triangles are assumed between the vertices in the triangular model, detailed surface structures, contained in the voxels, between the individual vertices, are not represented and therefore lost.

The extraction of a point cloud or a triangular model from the voxels corresponds to a scan of the object surface. The amount of data generally should be reduced for further processing. The quality or geometric precision of the triangular model depends on how well the triangles can reproduce the actual course of the material surface (e.g. chord error). Special software applications are used to reduce the number of triangles with minimal loss.

For each of these process steps, the involved losses shall be taken into account for the subsequent steps. Due to the special process conditions, the quality of the dimensional data shall be checked for plausibility and significance.

4.5.3.6 Nominal-actual comparison

A dimensional CT application is the comparison of the recorded part (actual object) with the nominal geometry from the CAD (or other sources). After registering the CT coordinate system with the CAD coordinate system, it is possible to compare the geometric deviation of the CT-measured actual part with the CAD specification of the nominal geometry using appropriate software. The nominal-actual comparison can be carried out between the exported STL model or the point cloud of the voxels and the CAD data or by directly comparing the voxels with the CAD data without prior STL or point cloud extraction.

4.5.3.7 Further processing of geometric data

CT can also be used for the non-destructive determination of geometric data (reverse engineering), e.g. of prototype parts or adjacent components.

CAD models are normally not based on triangular models, rather on geometric primitives (e.g. cylinder) and so-called free-form surfaces. For this reason, a further processing of the geometric data in CAD systems, for example, the engineering of the surface determined from the voxels in a CAD-established model, is required. With the appropriate software, triangular models can be transferred to CAD-compatible elements (so-called reverse engineering), whereby CT-examined objects, i.e. real geometries, can again be incorporated into the CAD process.

5 Parameters and procedures for acceptable results

5.1 Image quality parameters

5.1.1 Contrast

The quantity that is reconstructed during X-ray CT imaging is the linear attenuation coefficient, μ after calibration. It is measured in units of inverse length (e.g. mm^{-1}) and is approximately proportional to the electron density of the material. To be distinguishable, a feature shall have a linear attenuation coefficient, μ_f, sufficiently different from the linear attenuation coefficient of its background material, μ_b.

Linear attenuation coefficients are functions of the incident X-ray energy. For simplicity in these discussions, the X-rays used are assumed to have a single energy E, or to be approximated by some mean energy $\bar{E}$ if a spectrum of energy is used. If this is not known, a rule of thumb is to assume one third of the acceleration potential if the test object is weakly attenuating, or 2/3 if the test object is strongly attenuating.