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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 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).

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This document was prepared by the European Committee for Standardization (CEN) (as EN 16016-3) and was adopted, under a special "fast-track procedure", by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 5, *Radiographic testing*, in parallel with its approval by the ISO member bodies.

This first edition of ISO 15708-3 cancels and replaces ISO 15708-2:2002, of which it forms the subject of a technical revision. It takes into consideration developments in computed tomography (CT) and computational power over the preceding decade.

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

Non-destructive testing — Radiation methods for computed tomography —

Part 3:
Operation and interpretation

1 Scope

This document presents an outline of the operation of a computed tomography (CT) system and the interpretation of results with the aim of providing the operator with technical information to enable the selection of suitable parameters.

It is applicable to *industrial* imaging (i.e. non-medical applications) and gives a consistent set of CT performance parameter definitions, including how those performance parameters relate to CT system specifications.

This document deals with computed axial tomography and excludes 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 15708-1:2017, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Terminology*

ISO 15708-2:2017, *Non-destructive testing — Radiation methods for computed tomography — Part 2: Principle, equipment and samples*

3 Terms and definitions

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

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

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Operational procedure

4.1 General

For target-oriented computer tomography (CT) inspection procedures, the test and measurement tasks are defined in advance with regard to the size and type of features/defects to be verified; for example, through the specification of appropriate acceptance levels and geometry deviations. In the following, the process steps of a CT application are described and information on its implementation provided.

4.2 CT system set-up

4.2.1 General

The CT system set-up is oriented towards the requirements for the given task. The required spatial resolution (taking into account the tube focal spot size), contrast resolution, 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 is provided on setting up a CT system for inspection. Due to the interactions of the different system parameters, it may be necessary to run through the set-up steps several times in order to acquire optimal data.

The optimal energy is that which gives the best signal-to-noise ratio and not necessarily that which gives the clearest radiograph (the dependency of the detector efficiency on the energy is to be taken into account). However, in order to differentiate between materials of different chemical composition it may 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. In order to achieve high resolutions, the projection can be magnified onto the detector. The magnification is equal to the ratio of the source-detector distance to the source-object distance. Increasing source-detector distance leads to a reduced intensity at the detector and thus to a reduced signal to noise ratio. Accordingly, this also applies when using detectors with improved detector resolution, which can result in a reduction of the signal-to-noise ratio due to the reduced intensity per pixel. In general, for this reason, minimisation of the source-object distance is to be preferred.

In order to obtain high beam intensity at the detector, the source-detector distance should be selected so that it is as small as possible taking into account the required 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 15°, but this is specimen dependant, in order to minimise reconstruction-determined (Feldkamp) distortions of the 3D model. In addition, these restrictions do not apply for the perpendicular (in general horizontal) beam angle. For a higher geometric magnification, the object must be positioned as near as possible to the source, taking into consideration the limit on sharpness imposed by focal spot size. The rotation of the object must take place at at least 180 °plus beam angle of the X-ray beam, whereby an improved data quality is the result of an increasing number of angular increments. For this reason, the object is typically turned through 360 °. Ideally, the number of angular increments should be at least $\pi/2$ × matrix size (uneven number of projections per 360°) where the matrix size is the number of voxels across the sample diameter or the largest dimension. For more information, refer to 5.5.

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

In order to obtain as complete information as possible on the specimen, the requirement in general for a CT is that the object (or the interesting section of the object) is completely mapped in each projection on the detector. For large components that exceed the beam cone, a so-called measurement range extension is used. This measurement range extension is accomplished 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 only scan a part of the object (region-of-interest CT), which may lead to a restricted 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 image) must be corrected for in order to obtain a reconstruction which is as precise as possible. This can be achieved by careful realignment of the system or be corrected using software.

4.2.3 X-ray source

At the X-ray source, the maximum beam energy and tube current are to be set such that sufficient penetration of the test object and 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 15708-2:2017, 8.2. For the best measurement results, an attenuation ratio of approx. 1:10 should be used. That is the grey level through the sample should be about 10 % of the white level (both measured with respect to the dark level). The optimal range can be achieved through the use of pre-filters. It should be noted that every pre-filter reduces the intensity. Pre-filters have the additional advantage of reducing beam hardening, though further improvements can be made with software correction.

4.2.4 Detector

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

- exposure time (frame rate);
- number of integrations per projection;
- digitisation gain and offset;
- 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 detector properties: its geometric resolution, its sensitivity, dynamics and noise. The gain and exposure time can be adjusted together with the radiation intensity of the source so that the maximum digitised intensity 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 image and it is often limited by the time available for inspection.

4.3 Reconstruction parameters

The volumetric region to be reconstructed, the size of the CT image (in terms of voxels) as well as its dynamic range (which should take into account the detector dynamic range) shall be specified. In order to achieve sufficient CT image quality, 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 CT 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 image. In addition, it is possible to place user-defined sectional planes through the object in order to examine the internal structure, or to interactively visualise the CT image, for example by rotating and moving it as a 3D object. Image processing can be applied to CT images to improve feature recognition.

It may not be possible to load the whole CT image at full resolution into memory at once.

4.5 Analysis and interpretation of CT images

4.5.1 General

Typical 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 give rise to changes in CT grey level within the CT image. Analysis of CT images is performed by qualified personnel using software. A suitable contrast range or an automatic or manual calibration is used. The position, CT grey value and dimensions of features can be determined. Several tools are available for this, including manual ones or automatic tools such as strobe lines or gauges that engage at grey value thresholds or edges. For examining the structure and location of assembled components, a qualitative comparison of CT images without determination of the dimensions can suffice.

For an automatic determination using visualisation software tools (for example fault analyses), a calibration via the specification of a grey value range is, in general, required for the sample material to be measured. The specification of the grey levels can be done 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 from 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 (at the position of the sample).

4.5.3 Dimensional testing

4.5.3.1 General

Depending on the task, there are various methods currently in use for determining geometric features. Point-to-point distances can be manually determined 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 procedure, in which the dimensional measurement takes place in or is derived from CT images. 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 and
- 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 image.

4.5.3.2 Determination of precise image scale

The precise image scale or voxel size must be determined through the measurement of a suitable calibration standard (together with the measurement object and directly before/after the object inspection) or using a reference geometry at the object. For this, 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 M*. Thus, for example, the exact voxel size can be determined with high precision via measurements without the disturbing influence of other variables (for example, the precise position of the component surface (grey value threshold) in the CT image) for the centre distances of a test piece (e.g. dumbbell, see Figure 1). In this procedure, it must be taken into account that the CT grey values of the test item can, under certain circumstances, be influenced by the accompanying reference bodies (for example, through changes to the contrast ratios, interferences and artefacts). Using the actual voxel sizes determined in this way, the visualisation software can be correspondingly scaled/corrected as regards the voxel size specified by the system.

Figure 1 — Reference objects (dumbbell)

4.5.3.3 Threshold value determination

In order to be able to carry out dimensional measurements, the component surface or material contact surface must be determined in the CT image. The component surface is generally derived 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 may be specified globally for the entire CT image as an average grey value of, for example, the material and air. This is sometimes known as the “iso50 threshold”. A global threshold value or calibration using the iso50 method is suitable for many measurement tasks on objects made from homogeneous materials.

A global threshold is not suitable for objects made from several materials. In these cases, different thresholds should be used according to the materials either side of the boundary. Even in the case of objects made from homogeneous materials, beam hardening, scattering and other artefacts can result in local dimming or lightening in the CT image which would distort the measurement results. The grey value threshold, for example, for surfaces in the inside of the component thus frequently differs from that for surfaces on the outside of the component. The threshold can, if necessary, be determined locally from grey levels either side of the boundary. A determination of the overall component surface via locally determined threshold values, while more time consuming, is more tolerant towards contrast variations and artefact influences.

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 may be employed. In this connection, so-called geometric primitive bodies or reference elements (for example planes, cylinders, spheres or similar) are fitted, using software, to object contours of interest in the correspondingly calibrated data. At the reference elements, geometric features (for example, diameter, distances, angles, etc.) are determined directly or by combining reference elements. By fitting to the typically several thousand measurement points of the corresponding data, there is thus, due to the statistic averaging and reduction of the user influence, an often much 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-isosurface, 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 as to which vertices belong to a triangle. The vertices are 3D points, which lie on the threshold value-isosurface. The quantity of all vertices is also designated a point cloud. It is initially the linking information, i.e. the information as to which three vertices in each case form a surface triangle, which 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 in general important information on adjacent vertices is lost and if necessary must subsequently be reproduced.

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 can, under certain circumstances, not be represented and are thus lost.

The extraction of a point cloud or a triangular model from the voxels corresponds to a scanning of the object surface. For further processing, the amount of data must in general be reduced. The quality or geometric precision of the triangular model depends on how good the triangle can reproduce the actual course of the material surface (e.g. chord error). With special software applications, a low-loss reduction of the number of triangles is aimed for.

For each of these process steps, the involved losses are to be taken into account for the subsequent steps. Due to the special process conditions, the quality of the dimensional data is to 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, there is the option, via the appropriate software, of comparing the geometric deviation of the CT-measured actual component with the CAD specification of the nominal geometry. The nominal-actual comparison can be carried out between the exported STL model or the point cloud and the CAD data or by directly comparing the voxels with the CAD data without previous 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 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 Requirements for acceptable results

5.1 Image quality parameters

5.1.1 Contrast

The quantity that is reconstructed in X-ray CT imaging is the linear attenuation coefficient, μ. 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 reasonable rule of thumb would be one third of the accelerating potential if the test object is weakly attenuating or 2/3 if the test object is strongly attenuating.

Figure 2 shows the functional energy dependence of the X-ray linear attenuation coefficients of two hypothetical materials, μ_b and μ_f. $\Delta\mu$ is the difference in attenuation for these two materials:

$$\Delta\mu = |\mu_\mathrm{b} - \mu_\mathrm{f}| \tag{1}$$

Contrast in CT has been defined historically as the percent difference of a feature from a background material.

$$\text{Contrast:} \quad \Delta\mu\ (\%) = \frac{|\mu_\mathrm{b} - \mu_\mathrm{f}|}{\mu_\mathrm{b}} \times 100 \tag{2}$$

This definition for contrast assumes that the feature in question extends throughout the thickness of the CT slice. If the feature has thickness, h_f, but is imaged with a slice of larger thickness, h_s, the contrast is further reduced by the factor $h_\mathrm{f} / h_\mathrm{s}$ (partial volume effect).

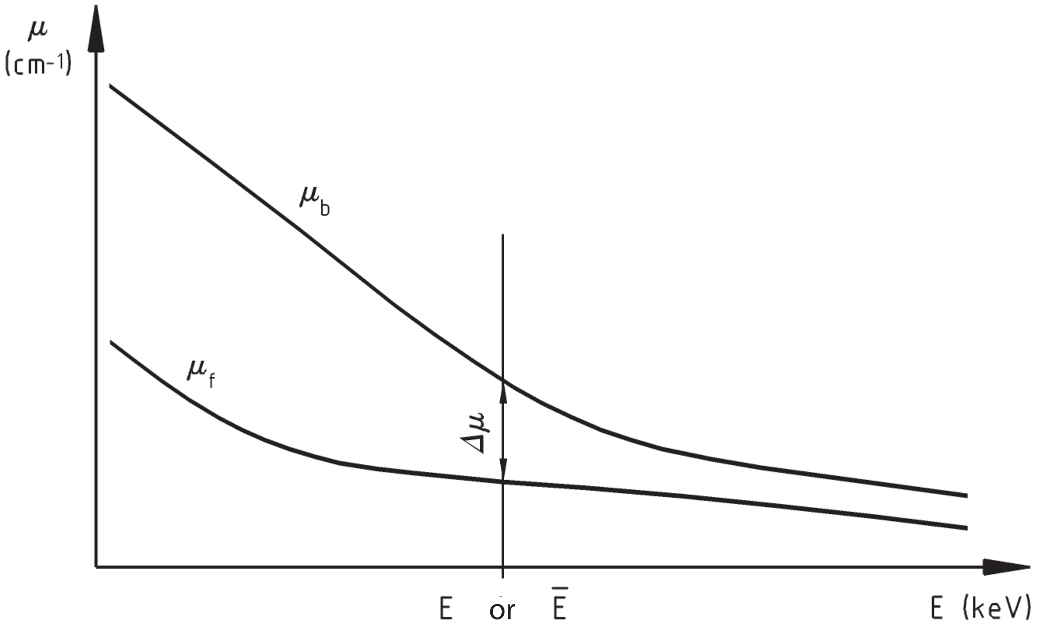

Figure 2 — $\Delta\mu$ as a function of X-ray energy

This difference $\Delta\mu$ and thus the contrast depends greatly on the X-ray energy, which is thus an important parameter. Choosing a low energy maximizes contrast but is detrimental to good detectability