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Nondestructive testing of pressure equipment - Part 15:

Phased-array ultrasonic testing

承压设备无损检测 第 15 部分：相控阵超声检测

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Nondestructive testing of pressure equipment - Part 15:

Phased-array ultrasonic testing

1 Scope

1.1 This document specifies the methods and quality grading requirements for phased-array ultrasonic testing of pressure equipment. The phased-array ultrasonic testing conducted in accordance with the relevant technical requirements of this document is a recordable pulse reflection ultrasonic testing.

1.2 This document is applicable to phased-array ultrasonic testing of metal raw materials, components, and welded joints during the production and use of pressure equipment.

1.3 For phased-array ultrasonic testing of polyethylene pipeline electric fusion joints, please refer to Annex A (informative).

1.4 For phased-array ultrasonic testing of materials, structures, and welded joints for pressure equipment not explicitly specified in this document, if it can meet the testing requirements through process verification, it can be executed in accordance with this document. The phased-array ultrasonic testing of supporting and structural components related to pressure equipment can also be carried out in accordance with this document.

2 Normative references

The following referenced documents are indispensable for the application 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.

GB/T 699, *Quality carbon structure steels*

GB/T 11259, *Non-destructive testing -- Practice for fabrication and control of steel reference blocks used in ultrasonic testing*

GB/T 12604.1, *Non-destructive testing -- Terminology -- Ultrasonic testing*

GB/T 29302, *Non-destructive testing instruments -- Characterization and verification of phased-array ultrasonic examination systems*

GB/T 29460, *Safety assessment for electrofusion joint of polyethylene pipes containing defects*

shall have a certain basic knowledge in metal materials, welding, heat treatment, and pressure equipment manufacturing and installation. For phased-array ultrasonic testing personnel engaged in other testing objects, they shall also have knowledge of relevant materials, structures, manufacturing processes, and sound field modeling, and undergo specialized training to possess the required technical abilities and corresponding testing experience.

4.2 Testing equipment and material

4.2.1 Testing equipment

The testing equipment includes testing instruments, as well as all objects such as probes, scanning devices, and cables connected to the instruments. Material refers to other devices and materials required to achieve testing functions that are not connected to the instrument, including test blocks and coupling agents. The performance of testing equipment and material shall meet the requirements of this document. The function shall meet the process requirements of the tested object.

4.2.2 Testing instruments and probes

4.2.2.1 The testing instrument shall have at least multi-channel ultrasonic emission, reception, amplification, automatic data acquisition, recording, display, and analysis functions. The instrument shall comply with its corresponding product standards and have product quality certification documents. The qualification certificate document shall at least include the preheating time, low voltage alarm or low voltage automatic shutdown voltage, transmission pulse repetition frequency, effective output impedance, transmission pulse voltage, transmission pulse rise time, transmission pulse width (using square wave pulse as the transmission pulse), transmission delay accuracy, amplifier frequency response, attenuator accuracy, dynamic range, and crosstalk as the main parameters. The electrical performance and basic functions of the instrument shall meet the requirements of Annex C (normative). Provide certification documents issued by a third-party laboratory accredited to ISO/IEC 17025 according to specifications and models. The data record transmission format of the testing instrument shall adopt the format specified in Annex B (informative).

4.2.2.2 The probe shall comply with its corresponding product standards. It shall have product quality certification documents. The qualification certificate document shall include at least the main parameters such as probe size, center frequency, bandwidth, impedance or static capacitance, number of array elements, first and last array element positions, array element spacing, inter element crosstalk, pulse echo sensitivity, etc. The performance indicators of the probe shall meet the requirements of Annex D (normative). Provide certification documents issued by a third-party laboratory accredited to ISO/IEC 17025 according to specifications and models.

4.2.2.3 Requirements for the performance of testing instruments, probes, and their combinations

4.2.3.2 Comparison test block

4.2.3.2.1 The comparison test block is mainly used for testing and calibration. According to their different production methods and uses, they can be divided into general reference blocks and specialized reference blocks. The reference reflector made by machining shall have a clear meaning in the comparison test block.

4.2.3.2.2 Universal reference block

- a) The geometric shape, size, and reference reflector setting of the universal reference block shall be in accordance with the corresponding content and drawings specified in this document. Its dimensional accuracy shall meet the requirements of JB/T 8428;
- b) The material used for making the universal reference test block shall be 20[#] high-quality carbon structural steel melted in an electric furnace or open hearth. The chemical composition meets the requirements of GB/T 699. After forging and forming, normalizing treatment is carried out to ensure uniform material without acoustic anisotropy. The grain size ranges from grade 7~8. When using a straight probe for testing, there shall be no defects greater than or equal to the equivalent diameter of a flat bottom hole of $\Phi 2$ mm.

4.2.3.2.3 Special comparison test block

- a) The material, external dimensions, and manufacturing process of the dedicated reference block are the same or similar to those of the tested workpiece;
- b) When using a straight probe for testing, there shall be no defects greater than or equal to the equivalent diameter of a flat bottom hole of $\Phi 2$ mm;
- c) The setting of reference reflectors can refer to the corresponding content and specifications in this document, and shall meet the requirements of testing, calibration, and equipment debugging;
- d) If used for process validation purposes as required in 4.3.3, the possible types, sizes, positions, and directions of defects in the tested workpiece shall also be considered. Corresponding reference reflectors shall be set.

4.2.3.3 Simulated test block

4.2.3.3.1 Simulated test blocks refer to test blocks containing simulated defects, mainly used for testing process validation.

4.2.3.3.2 The material and acoustic characteristics of the simulated test block shall be the same or similar to the tested workpiece, without any other defects that may affect the testing.

4.2.3.3.3 The external structure, thickness, and surface conditions of the simulated test

block shall be the same or similar to the tested workpiece.

4.2.3.3.4 For welded joints, simulated defects shall be prepared using welding methods or using real defects found in previous testing. For non-welded joint tested workpieces, their simulated defects shall have the shape of real defects and similar acoustic characteristics.

4.2.3.3.5 The type, location, size, and quantity of simulated defects shall be set considering the possible defect states that may exist in the tested workpiece. For welded joints, at least longitudinal and transverse defects, volumetric and area defects, surface and buried defects shall be included, and their dimensions shall generally not exceed the maximum allowable defect size of workpieces of the same thickness specified in grade II. They can be composed of one or more test blocks of the same thickness range.

4.2.4 Coupling agent

4.2.4.1 Coupling agent shall have properties that have good sound transmission and do not damage the surface of the tested workpiece, such as engine oil, chemical paste, glycerin, and water.

4.2.4.2 The coupling agent shall be stable and reliable within the temperature range specified in the process document.

4.2.5 Calibration, verification, operational verification, and testing of testing equipment

4.2.5.1 General requirements

Calibration, verification, operational verification, and testing shall generally be carried out using standard test blocks and comparative test blocks. During operation, the main sound beam of the probe shall be vertically aligned with the reflection surface of the reflector to obtain stable and maximum reflection signals. Controllers that affect instrument linearity, such as suppression or filtering switches, shall be placed in the "off" position or at the lowest grade.

4.2.5.2 Calibration or verification

At least once a year, calibrate and record the vertical linearity, horizontal linearity, attenuator accuracy, combination frequency, lateral and vertical resolution of sectorial electronic scanning imaging, as well as the range and resolution of sectorial electronic scanning angles in the performance of testing instruments and probe combinations. The testing requirements shall meet the provisions of 4.2.2.3.1.

4.2.5.3 Operational verification

4.2.5.3.1 Verify and record the vertical and horizontal linearity of the instrument and probe combination performance at least once every 6 months. The testing requirements shall meet the provisions of 4.2.2.1.

developed, and process validation shall be carried out according to 4.3.3.

4.3.2.3 General testing methods for different categories of testing objects

4.3.2.3.1 For the testing of raw material pipes, transverse wave oblique incidence testing is generally used. Add longitudinal wave direct injection testing if necessary. For the testing of other raw materials and component base materials, longitudinal wave direct injection testing is generally used. If necessary, increase the testing of oblique incidence of transverse or longitudinal waves.

4.3.2.3.2 For welded joints of pressure equipment, transverse wave oblique incidence testing is generally used. When the technical grade is C, longitudinal wave direct injection testing shall also be added.

4.3.2.4 Selection of testing surface

4.3.2.4.1 The selection of the testing surface shall comprehensively consider factors such as the structure of the tested workpiece, manufacturing process, possible locations and orientations of defects, and the operability of the testing implementation.

4.3.2.4.2 For welding joint testing, the grade of testing technology used shall also be considered.

4.3.2.5 General principles for selecting comparison test blocks

4.3.2.5.1 For ferritic steel raw materials, component base materials, or welded joints, universal comparison test blocks can be used.

4.3.2.5.2 For non-ferritic steel raw materials, components or welded joints, as well as ferritic steel workpieces with complex geometric shapes, specialized reference blocks are generally used. At this point, the size, quantity, and position distribution of reference reflectors within the test block shall be considered to meet the requirements of calibration and/or process validation.

4.3.2.6 General principles for setting process parameters

4.3.2.6.1 The probe (wedge) and testing area coverage method shall be comprehensively selected based on the type, material, structural size, testing surface, and testing method of the tested workpiece.

4.3.2.6.2 The parameters selected for phased-array probes include type, frequency, number of chips, chip spacing, and chip size. On the premise of obtaining stable coupling and sufficient signal-to-noise ratio, it is advisable to choose probes with higher frequencies and more chips as much as possible. For thin-walled workpieces, high-frequency and small active aperture probes are often used. For thick-walled workpieces, low-frequency and large active aperture probes are often used. For the testing of large-sized raw materials and components, linear array probes or area array probes with a large number of chips are often used. For dissimilar steel welded joints or austenitic

Δx - The set scan step value, mm.

4.3.2.7.4 Selection of coupling agents and surface temperature requirements for workpieces

The coupling agent used in actual testing shall be the same as the coupling agent used in the setting and calibration of the testing system. When using conventional probes and coupling agents, the surface temperature of the tested workpiece shall be controlled between 0°C~50°C. If the temperature exceeds 50°C or is below 0°C, special probes or coupling agents can be used. The difference between the setting and calibration of the testing system and the actual testing temperature shall be controlled within $\pm 15^\circ\text{C}$.

4.3.2.7.5 General requirements for coupling

During the scanning process, coupling stability shall be maintained. Effective monitoring of coupling situations shall be carried out when necessary. The setting of coupling monitoring can be determined based on the phased-array ultrasound equipment used. When poor coupling is found, the area shall be scanned again.

4.3.2.8 General requirements for testing images and data

4.3.2.8.1 The testing images generally include S-display, A-display, B-display, C-display, and D-display. Suitable display methods can be selected according to needs. For complex structures, defect states shall be displayed in the modeled structure.

4.3.2.8.2 There shall be position information in the image display. Angle information shall be provided during fixed-point testing.

4.3.2.8.3 Before analyzing data, the collected data shall be evaluated to determine its validity. The data shall at least meet the following requirements. If the data is invalid, it shall be corrected and re-scanned:

- a) The data is collected based on the scanning step setting (except for special circumstances such as fixed-point testing);
- b) The collected data shall be well coupled and the amount of data shall meet the requirements of the tested length;
- c) The amount of A-scan signal loss in each testing data shall not exceed 5% of the total amount. And the continuous loss length of adjacent A scan signals shall not exceed twice the maximum scanning step value specified in Table 2. The loss of scanning signal at defect location A shall not affect the evaluation of the defect.

4.3.2.8.4 When analyzing data, various displays shall be combined with the material, structure, and manufacturing characteristics of the tested object for comprehensive judgment. For welded joints, typical diagrams (partial) can be found in Annex E (informative).

including at least the minimum and maximum values of the workpiece specifications. And select corresponding test blocks for process validation:

- a) Testing of non-ferritic steel raw materials or component base materials with simple geometric shapes;
- b) Testing of ferritic steel for corner joints or T-joints according to technical grade A or B;
- c) Testing of martensitic or austenitic steel joints according to technical grade A or B;
- d) Testing of ferritic steel butt joints according to technical grade C.

4.3.3.3 In the following cases, a special comparison test block or simulated test block consistent with the workpiece to be tested [only simulated test blocks can be used for item b)] shall be made for process verification:

- a) Raw materials or parts with complex geometric shapes;
- b) Dissimilar steel welded joints formed by welding fine-grained and coarse-grained materials;
- c) Welded joints that cannot fully meet the requirements of the testing technical grade due to structural reasons;
- d) Non-orthogonal corner or T-joints;
- e) Other tested workpieces that do not fall within the scope of 4.3.3.1 and 4.3.3.2;
- f) When the contract technical requirements or relevant parties deem it necessary.

4.3.3.4 Ultrasonic simulation can also be used to replace process verification using special comparison test blocks or simulated test blocks. However, the simulation technology used shall be technically verified and tested on site to meet the actual testing requirements. Relevant certification documents shall also be provided.

4.3.3.5 The process validation results shall meet the following requirements.

4.3.3.5.1 All reference reflectors or defects in the test block shall be clearly visible.

4.3.3.5.2 The measured reference reflector or defect size deviation value is within the allowable range.

4.3.3.6 If necessary, a competent technical organization may be entrusted to conduct process validation and provide corresponding supporting documents.

4.4 General procedure for phased-array ultrasonic testing

45°;

- b) Probe parameter selection: the nominal frequency of the probe is generally 1MHz ~ 10MHz; the number of array elements for a single excitation must not be less than 16; refer to Table 23 for selection;
- c) Delay rule setting: when the testing sound range is below 50 mm, the focus depth can be set at the maximum testing sound range; when the testing sound range is above 50 mm, the focus depth can be selected at the middle value of the testing sound range or other appropriate depths;
- d) Electronic scanning settings: generally, linear electronic scanning is used. If necessary, sectorial electronic scanning can be used;
- e) Mechanical scan: use parallel lines or grid lines to achieve 100% coverage and is based on position sensor scanning and data collection.

5.5.2.6 The following descriptions in this clause, unless otherwise specified, refer to the method of direct incidence of longitudinal waves.

5.5.3 Probe and wedge selection

5.5.3.1 The nominal frequency of the probe is generally 1MHz ~ 10MHz. As the test thickness increases, a lower frequency probe shall be used.

5.5.3.2 The number of excitation array elements and the active aperture shall be selected according to the thickness of the forging. The number of array elements for a single excitation shall not be less than 8. If the test thickness $t \leq 250$ mm, refer to Table 6 for selection; when $t > 250$ mm, the active aperture area shall not be less than 320 mm². When performing small-angle longitudinal wave sectorial electronic scanning, the number of array elements for a single excitation shall not be less than 16. Refer to Table 23 for selection.

5.5.3.3 Flat wedges or films can be used in the direct contact method.

5.5.3.4 The probe shall have good contact with the test surface. When the gap between the probe wedge and the contact surface of the workpiece is greater than 0.5 mm, a curved wedge shall be used or the wedge shall be ground. When grinding, the geometric dimensions of the wedge shall be remeasured. At the same time, the impact on the sound beam shall be considered.

5.5.4 Delay law settings

Generally, the focus depth is set at 1~5 times the maximum sound path of the testing according to the testing thickness. When it is necessary to accurately quantify the defects or test a specific area, the focus depth can be set in this area.

5.5.5 Comparison test block

5.5.5.1 The comparison test blocks shall comply with the requirements of 4.2.3.2.

5.5.5.2 The universal test block CS-2 or CS-3 may be used. Its shape and size shall comply with the relevant provisions in NB/T 47013.3.

5.5.5.3 Special comparison test blocks CS-2 or CS-3 can also be made from the excess parts of the forgings being tested or materials with the same steel grade, heat treatment state, and processing method as the forgings being tested. Their shapes and sizes shall comply with the corresponding provisions in NB/T 47013.3. At least 3 groups or more of $\Phi 2$ mm, $\Phi 3$ mm, and $\Phi 4$ mm flat-bottom holes of different depths shall be set according to the testing thickness of the forgings being tested.

5.5.5.4 When the thickness of the tested part is greater than or equal to 3 times the near-field length of the probe, and the testing surface is parallel to the bottom surface, the tested workpiece can also be used as a comparison test block.

5.5.5.5 If necessary, other comparison test blocks may also be used.

5.5.5.6 When the radius of curvature of the workpiece test surface is less than or equal to 250 mm, a curved surface comparison test block (the curvature radius of the test block is within the range of 0.9~1.5 times the curvature radius of the workpiece) shall be used to adjust the reference sensitivity. Or a CS-4 comparison test block can be used to measure the sound energy loss caused by different curvatures. The shape and size of the test block shall comply with the provisions of NB/T 47013.3.

5.5.6 Imaging display mode

A-display, C-display, B-display or D-display are generally used.

5.5.7 A-scan time window setting

The start position of the A scanning time window shall be set at least 0.5 μ s before the reflected wave from the scanning surface. The end position of the time window shall be set at least 0.5 μ s after the reflected wave from the bottom surface of the workpiece.

5.5.8 Determination of sensitivity

5.5.8.1 When using a universal comparison test block, at least three groups of flat-bottom holes of different depths (including at least $\Phi 2$ mm and $\Phi 4$ mm) that are suitable for the wall thickness of the forging shall be selected in the test block. The sensitivity shall be set in TCG or DAC mode respectively. Then, coupling compensation, attenuation compensation and surface compensation shall be performed according to the actual conditions of the forging and the test block, and this shall be used as the benchmark sensitivity.

5.5.8.2 When using a special comparison test block, at least 3 groups of flat-bottom holes of different depths (including at least $\Phi 2$ mm and $\Phi 4$ mm) shall be selected in the test block. The sensitivity shall be set in TCG or DAC mode respectively. Then,

5.6.8 Sensitivity setting

5.6.8.1 When the thickness of the workpiece to be tested is less than or equal to 600 mm, it shall be calibrated on a flat-bottom hole test block of appropriate thickness and equivalent diameter based on the thickness of the ordered forgings and the required quality grade. The sensitivity shall be set in TCG or DAC mode based on the actual measured value.

5.6.8.2 When the thickness of the workpiece to be tested is greater than 600 mm, adjust the bottom wave to 80% of the full scale at the defect-free part of the forging. Use this as the reference sensitivity. If the testing surface is not parallel to the bottom reflective surface, the $\Phi 13$ mm flat bottom hole can also be used for sensitivity setting.

5.6.9 Scan

5.6.9.1 During testing, coupling compensation, attenuation compensation and surface compensation shall be performed according to the actual situation. This is used as the benchmark sensitivity.

5.6.9.2 The scan sensitivity shall be at least 6 dB higher than the reference sensitivity.

5.6.9.3 All tested areas of forgings shall be scanned from two mutually perpendicular directions. If full thickness testing cannot be carried out on one side, testing shall be carried out on both sides. The testing distance shall be at least 60% of the thickness. For disc-shaped or pie-shaped forgings, testing shall be carried out from at least one plane. If possible, scan from the circumferential surface as much as possible.

5.6.9.4 For linear array probes, the moving direction shall be perpendicular to the active direction. The distance between adjacent scanning lines shall be at least less than the maximum active aperture of the probe. Two adjacent scanning areas shall have a 10% overlap.

5.6.9.5 For cylindrical forgings and ring forgings, the entire outer surface (side and circumferential surface) can be scanned. When testing cylindrical forgings, when the ratio of length to diameter exceeds 6 or the axial length exceeds 600 mm, axial testing shall be performed from both end faces over the largest possible range. If the double-end testing cannot exceed half of the axial length due to attenuation or other reasons, the axial testing can be performed using the oblique incidence of shear waves instead of the direct incidence of longitudinal waves.

5.6.9.6 It is recommended to use a two-dimensional dual-axis position encoder. The collected data shall contain the two-dimensional plane position information of the workpiece.

5.6.10 Defect record

5.6.10.1 Due to the existence of defects, the bottom wave under the reference sensitivity

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