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GUIDELINES FOR THE APPLICATION OF TIME-OF-FLIGHT DIFFRACTION (TOFD) AND PHASED ARRAY ULTRASONIC TESTING (PAUT) TECHNIQUES

2017

CONTENTS

CHAPTER 1 GENERAL

1.1 Purpose

1.1.1 These Guidelines provide technical references for review of testing procedures, on-site supervision and test data interpretation with regard to TOFD and PAUT techniques in order to advocate and promote the wide application of new NDT techniques.

1.2 Scope of application

1.2.1 These Guidelines apply to NDT for the internal quality of materials, structural members and weld joints during the construction, repair, operation or service of ships, offshore engineering or other steel structures.

1.2.2 These Guidelines apply to carbon steel or low-alloyed steel in ISC Rules for Materials and Welding. For other fine grained, isotropic or low attenuation metal materials, these Guidelines may also be referred to. For materials not complying with the above requirements, after test validation and ISC approval, the PAUT technique may also be used for testing of aluminum and its alloys, austenitic stainless steel, ferritic-austenitic stainless steel, titanium alloys as well as weld joints.

1.2.3 The TOFD technique is applicable to quality testing of full penetration weld joints with the base metal thickness≥10 mm, and is only applicable to plate butt or pipe butt welds.

1.2.4 The PAUT technique is applicable to quality testing of full penetration weld joints with the base metal thickness≥6 mm, and is applicable to plate butt, pipe butt, T-joint or angle joint welds.

1.2.5 For base metal thickness not complying with the requirements of 1.2.3 and 1.2.4, after test validation and ISC approval, the PAUT and TOFD techniques may also be used for testing of full penetration weld joints of other base metal thickness.

1.2.6 The PAUT and TOFD techniques are applicable to the longitudinal weld of shell with outside diameter greater than 250 mm or the ratio of inside and outside diameters greater than 0.7, circumferential weld of shell with outside diameter greater than 200 mm and curved plate full penetration weld of all sizes. For welds not complying with the requirements above, after test validation and ISC approval, the PAUT or TOFD technique may also be used for testing.

1.2.7 The PAUT technique is applicable to the base metal or structural member tested by ultrasonic A-scan pulse reflection technique specified by ISC Rules for Materials and Welding. However, each wave beam of scanning is to comply with the technical requirements in relevant standards of the ultrasonic A-scan pulse reflection technique, and the spacing of adjacent beams is not to be greater than the probe scanning spacing specified in the standards.

1.3 Organization and personnel requirements

1.3.1 Organization requirements

1.3.1.1 Relevant requirements of ISC for certification and approval of NDT organizations are to be complied with.

1.3.2 Personnel qualifications

1.3.2.1 Personnel engaged in TOFD and PAUT testing are to have the NDT qualification certificate issued or approved by ISC before carrying out testing activities corresponding to their qualification level. For details, see ISC Rules for Qualification and Certification of Non-Destructive Testing Personnel.

1.4 Class notation

1.4.1 When the following welds are tested by TOFD or PAUT, if the testing percentage complies with the following requirements, the corresponding notations may be assigned upon application by the ship owner.

TOFD(20%): the percentage of welds inspected by TOFD is more than 20%.

TOFD(40%): the percentage of welds inspected by TOFD is more than 40%.

TOFD(70%): the percentage of welds inspected by TOFD is more than 70%.

PAUT(20%): the percentage of welds inspected by PAUT is more than 20%.

PAUT(40%): the percentage of welds inspected by PAUT is more than 40%.

PAUT (70%): the percentage of welds inspected by PAUT is more than 70%.

Testing extent of container ships: all block-to-block butt joints of all upper flange longitudinal structural members in the cargo hold region (thickness≥35 mm), including the topmost strakes of the inner hull/bulkhead, the sheer strake, main deck, coaming plate, coaming top plate, and all attached longitudinal stiffeners.

Testing extent of ore carriers: butt welds of the main deck in the cargo area (thickness≥35 mm); full penetration welds between the longitudinal bulkhead and inner bottom plating; full penetration weld connections between lower stool and the inner bottom plating; full penetration weld connections between the lower stool slope plate and lower stool shelf plate; full penetration weld connections between the lower stool shelf plate and transverse bulkhead.

Testing extent of LNG and LPG carriers: full penetration welds of integral tanks or independent tanks, excluding membrane tanks weld.

Note: For time-of-flight diffraction (TOFD) technique, the testing extent excludes fillet weld.

1.5 Terms and definitions

1.5.1 Terms and definitions used in these Guidelines are as follows:

(1) Time-of-Flight Diffraction (TOFD) Technique

An ultrasonic testing technique using one or more pairs of longitudinal wave angle probes with wideband short pulse and large divergence angle to transmit and receive signals consecutively so as to detect and size up flaws mainly relying on the time of arrival of the diffraction wave signals.

(2) Phased Array Ultrasonic Testing (PAUT)

An ultrasonic testing technique based on the set focal law to apply different time delay (or voltage) when each element of the phased array probes is transmitting or receiving sound beam thus realizing the functions of testing the movement, deflection and focusing of the sound beam by forming wave beam.

(3) Probe center separation (PCS)

The straight-line distance between the index points of the transmitting and receiving probes.

(4) Parallel scan

A scan whereby the probe pair motion is parallel to the beam axis, generally for accurate positioning and sizing up of the known flaws.

(5) Non-parallel scan

A scan whereby the probe pair motion is perpendicular to the beam axis, generally referring to the scan whereby the probes are symmetrically located on both sides of the centerline of the weld.

(6) Offset non-parallel scan

An asymmetric scan whereby symcenter of the probes is at a certain distance from the centerline of the weld.

(7) Linear Scan/ Electronic Scan (E-Scan)

A scan applying the same focal law on various element groups of the phased array probes such that each group of the excited elements generates sound beam at a specific angle. The sound beam moves forward and aft ward along the element array by changing the position of the initial excited element so as to realize the testing results similar to moving conventional ultrasonic testing probes forward and aft ward manually.

(8) Sectorial scan (S-scan)

A scan using certain law of time delay to excite part of adjacent elements or all elements in the phased array probes so that the sound beam formed by the excitation element group scans the sectorial area by changing the angle at certain increment within the set angle range. The data display is in the form of 2D images formed by delaying and angle correcting A-scans of each angle.

(9) Focal law

An algorithm or relevant procedures to realize beam deflection and focusing by controlling the number of excitation elements as well as the transmitting and receiving delay applied to each element.

CHAPTER 2 TOFD TECHNIQUE

This Chapter gives the method for testing and assessment of flaws using the TOFD technique and specifies the basic requirements for testing system, procedure design, calibration, on-site data acquisition, data interpretation, testing report, etc. Appendix 1 explains in details the limitation of the TOFD technique in application.

2.1 Testing system

TOFD testing system includes ultrasonic instrument, software, probes/wedges, scanning mechanisms, blocks and other accessories. Reference is made to Figure 2.1. The above system is to be furnished with a product quality certificate or a quality document issued by the manufacturer and the ultrasonic instrument is to be within the valid calibration period.

In addition to complying with the requirements of this Chapter, TOFD testing system is also to satisfy the relevant requirements of JB/T10061 and CB/T3559.

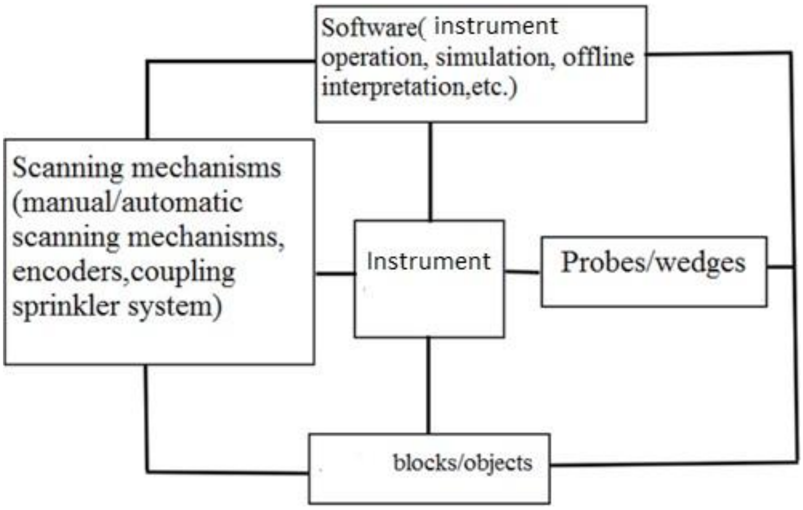


Figure 2.1 Composition of the Testing System

2.1.1 Ultrasonic instrument

2.1.1.1 Pulsers are to comply with the following requirements:

(1) The transmitting pulse can either be unipolar, bipolar sharp or square. The rise time is not to exceed 0.25 times the period corresponding to the nominal probe frequency.

(2) The pulse width of the equipment is to be tunable to allow optimization of pulse amplitude and duration. The pulse width adjusting increment is not to be more than 10 ns.

(3) The pulse repetition frequency of the equipment is to be tunable with the maximum value not less than 500 Hz.

(4) The equipment is to have sufficient voltage to ensure the testing system have sufficient sensitivity and signal-to-noise ratio.

2.1.1.2 Signal receivers are to comply with the following requirements:

(1) The receiver bandwidth is not to be less than the nominal probe bandwidth, normally not less than 0.8 MHz to 15 MHz.

(2) The system is to have sufficient gain which is to be continuously adjustable in increment of 1 dB or less.

(3) Since diffracted signal amplitudes are relatively low during the TOFD testing, a pre-amplifier may be added when the signal-to-noise ratio is insufficient.

2.1.1.3 Digitization is to comply with the following requirements:

(1) Digitized sampling frequency of RF signal is at least to be four times the nominal probe frequency. Where post-treatment is required for digital signal, digitized sampling frequency is at least to be eight times the nominal probe frequency.

(2) Sampling digit is at least to be 8.

(3) The number of grey scales is at least to be 256.

(4) Initial delay of A-scan signal is to be programmable between 0 and 200μs, and window length is to be programmable between 5 and 100μs.

(5) The equipment is to be capable of performing signal averaging, the maximum averaging number being not less than 8.

(6) The equipment is to have data acquisition function based on position encoding.

2.1.2 Software

2.1.2.1 The software is to include algorithms to linearize depth cursors or permit depth estimations.

2.1.2.2 The software is to be capable of copying all collected raw data in a tamper-proof manner.

2.1.2.3 The software is to be capable of processing data (such as lateral wave synchronization, lateral wave differentiation, SAFT, etc.) without changing the raw data.

2.1.3 Probes

2.1.3.1 In general wide longitudinal wave angle beam probes are to be used for testing.

2.1.3.2 TOFD testing is generally to use specialized TOFD probes. However, phased array, EMAT or other non-standardized probes may be used if they satisfy the application requirements.

2.1.3.3 The error between the nominal center frequency and measured frequency of probes are to be less than 10%.

2.1.3.4 The bandwidth of the probes at -6dB is not to be less than 80%.

2.1.3.5 The pulse width of the lateral wave at -20dB is not to exceed two cycles.

2.1.4 Wedges

2.1.4.1 Where the contact method is used for TOFD testing, the wedges at both sides are to have the same refraction angle. However, wedges of different refraction angles may also be used for special geometry if the validation is satisfactory.

2.1.4.2 TOFD wedges are to be marked with theoretical beam exit point.

2.1.4.3 The probes are mounted on the wedges. The coupling condition is to be good and stable.

2.1.4.4 For scanning surface having a curvature radius less than 150 mm, a corresponding curved wedge is to be used to guarantee coupling. And the curved surface of the wedge is to ensure that the maximum clearance between the wedge and the object is not greater than 0.5 mm.

2.1.5 Blocks

2.1.5.1 TOFD blocks are generally to include dead zone blocks, reference blocks, etc. Dead zone blocks are used to measure the top and bottom surface dead zones while reference blocks are used to identify system sensitivity or testing capability.

2.1.5.2 The reference block is to be made of materials with same or similar acoustic performance to the test object. For zones inside the block where the ultrasonic beam might pass through, flaw equivalent ≥ Φ2 mm flat bottom hole is not allowed.

2.1.5.3 Reference blocks are to have thickness from 0.8 to 1.5 times the object thickness with the maximum difference not exceeding 250 mm. The maximum thickness of the blocks is to guarantee that the direct reflected beam angle from the bottom surface center of the blocks is not less than 40°. The minimum thickness is to guarantee that the theoretical beam intersection of both probes is inside the blocks.

2.1.5.4 For objects having a curvature radius not greater than 150 mm, a curved reference block is to be used. Curved reference blocks are to have curvature radius from 0.9 to 1.5 times the object curvature radius. For objects having a curvature radius greater than 150 mm, a flat reference block may be used.

2.1.5.5 Reference blocks are to be made according to the requirements of Appendix 3. Dead zone blocks may be made according to the requirements of Appendix 3 or blocks of similar functions may be used.

2.1.6 Scanning mechanisms and encoders

2.1.6.1 The scanning mechanism is to guarantee that the TOFD probes maintain a constant PCS.

2.1.6.2 Probe motions and encoder signals are to be synchronized during manual or semi-automatic testing.

2.1.6.3 During automatic testing, motor-controlled signals are in general not to be used as encoder signals, unless there are feedback mechanisms ensuring that the encoder signals and the A-scan signals of the current probe position are synchronized.

2.2 Design of testing procedures

2.2.1 Testing specifications

2.2.1.1 TOFD testing procedure specifications are mainly to include the following:

(1) determining testing purpose (testing task, testing position, referenced standards, testing levels, acceptance levels, etc.);

(2) determining scope of the product (object size, specification, material, wall thickness, welding procedures, etc.)；

(3) procedure design (computer model, probe/wedge, scanning mechanism, block, PCS, dead zone and additional testing for transverse flaw);

(4) parameter setting and calibration;

(5) procedure validation;

(6) testing preparation;

(7) scanning and data acquisition;

(8) data analysis and interpretation;

(9) flaw evaluation and quality classification.

2.2.2 Testing levels

2.2.2.1 Testing levels include the following:

(1) There are four testing levels (A, B, C and D). From testing level A to testing level D an increasing reliability is achieved. For detailed requirements, see Table 2.2.2.1.

(2) Level A is only applicable for wall thicknesses up to 50 mm.

(3) For in-service inspections, only testing level D is to be applied.

(4) Where acceptance criteria require accurate measurement of flaw and position, procedures are to be made according to level D testing requirements.

Testing Levels **Table 2.2.2.1**

Testing levels	TOFD setup	Reference block for setup verification	Reference block for sensitivity settings	Offset scan	Written test procedure
A	As in Table 2	No	No	No	No
B	As in Table 2	No	Yes	No	No
C	As in Table 2	Yes	Yes	a	Yes
D	As defined by specification	Yes	Yes	a	Yes
a: The necessity, number and position of offset scans have to be determined.					

2.2.3 Testing coverage area

2.2.3.1 Testing coverage area is to comply with the following requirements:

(1) The height of the testing coverage area is to be the height of the object.

(2) The width of the testing coverage area is to be the weld and base metal for at least 10 mm on each side of the weld or the width of the heat-affected zone, whichever is greater.

(3) For re-testing or accurate sizing of the known flaw, the testing area may be reduced appropriately as necessary.

(4) The testing area is to be indicated in the testing report.

2.2.4 Testing procedure parameters

2.2.4.1 Testing procedure parameters are to comply with the following requirements:

(1) For base metal thickness up to 50 mm, a single pair of TOFD probes can be used. For base metal thickness greater than 50 mm, the wall thickness is to be divided into more than one inspection zone as the coverage of one pair of probes is insufficient. The recommended number of TOFD setups and testing techniques are shown in Table 2.2.4.1.

(2) TOFD probes used as one pair are to have same nominal frequency and element size. Detailed parameters are to be selected according to the thickness of the base metal or the depth and thickness of the zones. Recommended parameters are shown in Table 2.2.4.1.

(3) The wedge angle and PCS are correlated parameters. The wedge angle and PCS value selected are to cover the acoustic field of the testing area. In general, the wedge angle selected is to be such that included angle between the transmitting and receiving sound beams of flaw tip is about 120°. When this angle is reduced to below 90 or increased to more than 165, the diffracted echoes will be weak and this is to be avoided.

(4) As the upper spread angle is greater than the lower spread angle for angle probe, the intersection point of the transmitting and receiving beams are to be set in position lower than the testing area center, usually at 2/3 depth of the testing area depth, to calculate the wedge angle and the PCS value.

(5) To measure the known flaw accurately, the wedge angle is recommended to be 55 to 60 degrees, and the transmitting and receiving beam center lines are to intersect in the depth region where flaws are expected.

TOFD Setups for Simple Butt Welds of Wall Thickness Ranging from 10 mm to 400 mm **Table 2.2.4.1**

Thickness t (mm)	Number of TOFD setups	Depth range (mm)	Probe frequency (MHz)	Beam angle α (°)	Element size (mm)
⩾10~15	1	0~t	15~7	70~60	2~4
＞15~35	1	0~t	10~5	70~60	2~6
＞35~50	1	0~t	5~3	70~60	3~6
＞50~100	2	0~2t/5	7.5~5	70~60	3~6
		2t/5~t	5~3	60~45	6~12
＞100~200	3	0~t/5	7.5~5	70~60	3~6
		t/5~3t/5	5~3	60~45	6~12
		3t/5~t	5~2	60~45	6~20
＞200~300	4	0~40	7.5~5	70~60	3~6
		40~2t/5	5~3	60~45	6~12
		2t/5~3t/4	5~2	60~45	6~20
		3t/4~t	3~1	50~40	10~20
＞300~400	5	0~40	7.5~5	70~60	3~6
		40~3t/10	5~3	60~45	6~12
		3t/10~t/2	5~2	60~45	6~20
		t/2~3t/4	3~1	50~40	10~20
		3t/4~t	3~1	50~40	12~25

2.2.5 Types of scanning

2.2.5.1 Types of scanning are to comply with the following requirements:

(1) In general non-parallel scan is used for testing.

(2) Off-set non-parallel scan can reduce the testing dead zone of the bottom surface. For testing of level C and above, non-parallel scan and off-set non-parallel scan must be used for testing.

(3) For accurate depth and height measurement of the flaw, parallel scan must be carried out at the flaw position.

2.2.6 System parameter settings

2.2.6.1 PCS setting is to comply with the theoretical values calculated in accordance with Table 2.2.4.1 to adjust the PCS of the probes and set the system.

2.2.6.2 The parameters for pulsers and signal receivers are to comply with the following requirements:

(1) Excitation voltage setting: to obtain good signal-to-noise ratio, excitation voltage is in generally to be high voltage; where the sensitivity and signal-to-noise ratio is adequate, low voltage is also allowed to protect probes.

(2) Pulse width: pulse width is to be adjusted taking into consideration the probe frequency, lateral wave width, testing sensitivity and signal-to-noise ratio.

(3) Pulse repetition frequency: pulse repetition frequency is to be as high as possible to adapt to the relative fast testing speed. However, ghost echo brought by too high pulse repetition frequency is to be avoided.

(4) Filter setting: band pass, high pass or low pass filters may be used to improve the signal-to-noise ratio.

(5) Wave detection method: unrectified RF signals are used.

2.2.6.3 Digitized parameters are to comply with the following requirements:

(1) Sampling frequency: at least to be four times the nominal probe frequency. Where post-treatment of the data is required, sampling frequency is at least to be eight times the nominal probe frequency.

(2) Sampling digit: at least 8.

(3) Signal averaging: to reduce random noise and to increase signal-to-noise ratio, signal averaging is allowed for TOFD testing.

2.2.6.4 Indication scope is to comply with the following requirements:

(1) For testing using only one setup of TOFD, A-scan signal is to start at least 0.5 μs prior to the time of arrival of the lateral wave, and extend at least 0.5 μs beyond the back-wall signal. As the transverse signals in the wave-converted area may show the flaw signals in the surface or the back wall, the signals are to end 0.5 μs beyond the first mode-converted back-wall signal.

(2) If more than one setup of TOFD is used, the A-scan signal of the first zone is to display 0.5 μs prior to the time of arrival of the lateral wave and the display of the last zone is to end 0.5 μs beyond the first mode-converted back-wall signal. The time windows are to overlap by at least 25 % in the depth direction.

2.2.6.5 Image selection is to comply with the following requirement:

TOFD display is to include A-scan signals and gray-scaled B-scan images as a minimum.

2.2.6.6 Sensitivity setting is to comply with the following requirements:

(1) To ensure that the flaw signal falls in the range of the digital converter, the noise signal is to be limited such that the ultrasonic signal is greater than the electrical noise signal.

(2) Instrument settings (including electrical noise restriction and system gain) are to be adjusted to the electrical noise prior to the arrival of the lateral wave, which is at least 6dB lower in amplitude than the electrical noise after the arrival of the lateral wave in the baseline area. The latter noise is preferably to be set at 5% of the amplitude range.

(3) Sensitivity setting may refer to the representative flaws as well as artificial flaws of the reference blocks in Appendix 3, to obtain reasonable gain setting and signal-to-noise ratio.

(4) For A level testing, the sensitivity can be set on the test object directly. The amplitude of the lateral wave in parts free of flaw is to be between 40% and 80% full screen height (FSH) as the testing sensitivity. Where the lateral wave is invisible, the back wall is to be adjusted to 80% full screen height (FSH) plus 20 to 32dB. Where both are invisible, the material grain noise is to be adjusted to 5% to 10% full screen height (FSH).

(5) For testing of B level or above, reference blocks are to be used to adjust the sensitivity. Relatively weaker diffracted wave signal on the blocks are adjusted to between 40% and 80% full screen height (FSH) as the testing sensitivity. During actual testing, coupling compensation is to be added. The coupling compensation value is to be in accordance with the coupling compensation measurement of the ultrasonic A-scan pulse reflection technique.

(6) After the completion of the sensitivity setting, the electrical noise signal is not allowed to be greater than 5% full screen height (FSH).

2.2.6.7 Scan setting is to comply with the following requirements:

(1) Data recording length is to be set as the actual scanning length plus 20 to 30 mm. When scanning circumferential welds or continuous scanning of long welds, the actual scanning length is to be the weld length plus 20 mm.

(2) The scanning increment or resolution is set according to the plate thickness of the object. For detailed values see Table 2.2.6.7.

Scanning Resolution **Table 2.2.6.7**

Plate thickness t/mm	Maximum scanning increment/mm
$10 \le t < 150$	1.0
$t \ge 150$	2.0

2.2.6.8 Parameter setting examination is to comply with the following requirements:

(1) For testing of B level or above, the equipment sensitivity and top-surface dead zone are to be confirmed on the block prior to testing.

(2) For confirmation of the sensitivity, the reference block is used and the signal amplitude of the flaw is to be within 40% and 80% full screen height (FSH).

(3) For confirmation of the dead zone on the top surface, a dead zone block is used to find out the identifiable signal of the side-drilled hole with the minimum depth. The embedded depth of the side-drilled hole is considered to be the dead zone on the top surface and is to be recorded in the report.

2.3 Calibration

2.3.1 Wedge delay and sound velocity testing

2.3.1.1 For wedge delay testing, the bottom surfaces of two wedges with probes mounted may contact each other. Change the relative position of the wedges to obtain the maximum echo. The wedge delay is obtained by testing the echo duration.

2.3.1.2 Sound velocity testing is to be carried out on blocks of similar material to the object. Where necessary, validation may be carried out on the object.

2.3.2 Linearity of depth coordinate

2.3.2.1 To ensure converting time coordinates into depth coordinates, for the TOFD system, the linearity of coordinates is to include the following six variables:

(1) the wedge delay time t_0;

(2) the arrival time of the lateral wave t_L, $t_L = 2t_0 + 2t_1$;

(3) the arrival time of the reflector echo t_R, $t_R = 2t_0 + 2t_2$;

(4) the transmitting speed of the sound wave in the object V_L;

(5) the reflector depth H (in general the bottom surface of the block is to be taken as the reflector; in that case H is the plate thickness T of the object);

(6) distance S between beam exit points.

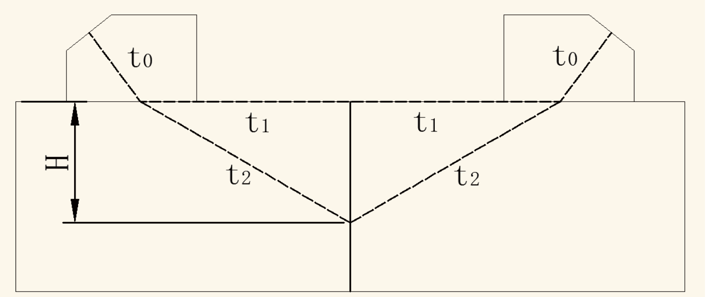


Figure 2.3.2.1 Illustration of Linearity of Depth Coordinates for TOFD Testing

The relations of each parameter may be indicated by the formulae below:

$$(t_L - 2t_0)V_L = S \qquad ①$$

$$(t_L - 2t_0)^2V_L^2 + H^2 = (t_R - 2t_0)^2V_L^2 \qquad ②$$

As both t_L and t_R can be measured by instrument, the objective of coordinate linearity is to determine the other four variables. In this way the system can calculate the actual height h value at any time t_x according to formula ③.

$$(t_L - 2t_0)^2 V_L^2 + h^2 = (t_x - 2t_0)^2 V_L^2 \qquad ③$$

To sum up, the system has two independent formulae and four variables. Consequently, measure any two variables of the four variables and calibrate other variables by formula, there are altogether six calibration methods. For details see Table 2.3.2.1. In actual application, appropriate calibration methods are to be selected taking into consideration the possible measurement errors of each measured value.

Linearity Method for Depth Coordinates in TOFD Testing Table 2.3.2.1

Method	Measured value	Calibrated value
1	Wedge delay t_0, PCS value S	target reflector depth H, sound velocity V_L
2	Wedge delay t_0, sound velocity V_L	target reflector depth H, PCS value S
3	Wedge delay t_0, target reflector depth H	sound velocity V_L, PCS value S
4	PCS value S, sound velocity V_L	target reflector depth H, wedge delay t_0
5	PCS value S, target reflector depth H	sound velocity V_L, wedge delay t_0
6	sound velocity V_L, target reflector depth H	Wedge delay t_0, PCS value S

(7) After depth linearity calibration, the depth measurement error on the block is not to be greater than 0.2 mm.

(8) For longitudinal welding joints of curved objects or other nonplanar objects, the depth calibration results are to be appropriately compensated.

2.3.3 Calibration of encoders

2.3.3.1 Calibration of encoders is to comply with the following requirements:

(1) The encoder is to be calibrated each time prior to use.

(2) During calibration of encoders, the moving length is not to be less than 500 mm, and the measurement error of the calibrated encoders is not to be greater than 1%.

2.4 On-site data acquisition

2.4.1 Surface conditions

2.4.1.1 During data acquisition, the surface conditions are to comply with the following requirements:

(1) The scanning surface on which the probes move is to be machined even and be free of weld spatter, rust, grease as well as other foreign matter that may interfere with the transmission of the acoustic energy. For the polished surface, the surface roughness R_a is not to be greater than 12.5 um. For the machined surface, the surface roughness R_a is not to be greater than 6.3 um.

(2) During off-set non-parallel scan or parallel scan, weld reinforcement in the corresponding testing area is generally to be removed so as to be flush with the base metal on both sides.

(3) Where there are relatively large pits on the scanning surface, patch welding is to be carried out and the patched area is to be made flush with the adjacent base metal.

2.4.2 Marking of testing position and testing direction

2.4.2.1 Marking of testing position and testing direction are to comply with the following requirements:

(1) The testing position is to give permanent reference position according to information on the weld and structure to ensure the traceability and reproducibility of the data.

(2) Specific rules are to be developed for the scanning direction of the weld. For example, the deck weld is to be scanned from the port side to the starboard side, the side weld from top to bottom, the longitudinal weld from stern to stem, etc. Those contents are to be specified in the testing procedures.

(3) During non-parallel scanning, a reference line is to be drawn according to the weld centerline with scanning motion marked so as to ensure that the probes move along the expected scanning plan.

(4) During parallel scanning, a scanning reference line is to be drawn with scanning motion marked.

2.4.3 Testing of base metal

2.4.3.1 Testing of base metal is to comply with the following requirements:

(1) Vertical beams are used to test the base metal, and correct determination of signals is to be guaranteed.

(2) For the testing of important objects, vertical beam testing is to be carried out on base metal area where the ultrasonic beams pass through. Reflections affecting testing results are to be recorded.

(3) When vertical beams are used to test the base metal, back wall echo of the object is to occur twice as a minimum. The second echo in way of position without flaw is set as 100% full screen height to test sensitivity. For areas where the flaw signal amplitude is more than 20% or where the echo disappears, the surface of the object is to be marked and recorded.

2.4.4 Couplants

2.4.4.1 The use of couplants is to comply with the following requirements:

(1) The couplant is to maintain stable and reliable ultrasound characteristics in the operating temperature range.

(2) The couplant is not to be harmful to operators, the tested objects and environment.

(3) The couplant used on site is to be the same as that used for calibration.

2.4.5 Temperature

During data acquisition, the temperature is to comply with the following requirements:

(1) When using conventional probes and couplants, the surface temperature of the object under examination is to be in the range of 0°C to 50°C.

(2) The temperature for calibration is to be within 20°C deviation from the temperature on site.

(3) Where the surface temperature of the object exceeds the range, special couplants and probes are to be used, and the set-up and calibration are to be carried out under the actual testing temperature.

2.4.6 Scanning and data acquisition

2.4.6.1 The scanning speed is to comply with the following requirements:

The maximum scanning speed is related to the pulse repetition frequency, the number of signal averaging and the scanning resolution. The actual scanning speed is not to be greater than the maximum scanning speed, and the data quality collected is to comply with the requirements of 2.6. The maximum scanning speed $V_{\max}$ is calculated according to the following formula:：

$$V_{\max} = \frac{PRF}{N}\Delta x$$

where: $V_{\max}$ — the maximum scanning velocity, in mm/s;
PRF — the pulse repetition frequency of the excitation probe, in Hz;
N — the number of signal averaging;
Δx — the scan increment, in mm.

2.4.6.2 Scanning coverage is to comply with the following requirements:

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

2.4.6.3 Scanning deviation is to comply with the following requirement:

During non-parallel scanning and off-set non-parallel scanning, the deviation between the actual scanning track and the theoretical one is not to be greater than 10% of the PCS.

2.4.6.4 Re-scanning is to comply with the following requirements:

(1) where the data quality is unsatisfactory, scanning is to be carried out according to paragraph 2.6.1;

(2) where the deviation of the scanning length of B-scan relative to the actual length exceeds 1% of the scanning length or 5 mm, whichever is lesser;

(3) where the scanning offset exceeds the requirements of 2.4.6.3, re-scanning is to be carried out.

2.4.6.5 Checking of the system is to comply with the following requirements:

(1) The system is to be checked at least every 4 h.

(2) Checks are to be carried out on completion of each testing or whenever a system parameter is changed.

(3) Where a reference block was not used, but instead the component was used for checking, then subsequent checks are to be carried out at the same position as the initial check. If a reference block was used for the initial setup, the same reference block is to be used for subsequent checks.

(4) Where deviations in Table 2.4.6.5 occur when the system is tested, settings are to be corrected and all tests carried out since the last valid check are to be repeated.

System Checking Requirements **Table 2.4.6.5**

Sensitivity	
Deviations ≤ 6 dB	Data may be corrected by software
Deviations＞6 dB	Settings are to be corrected and all tests carried out since the last valid check are to be repeated
Range	
Deviations ≤ 0.5 mm or 2 % of depth range, whichever is greater	
Deviations ＞0.5 mm or 2 % of depth range, whichever is greater	Settings are to be corrected and all tests carried out since the last valid check are to be repeated

2.4.6.6 Supplementary testing is to comply with the following requirements:

(1) For TOFD testing of the dead zone on the top surface, supplementary testing may be carried out using MT, ultrasonic A-scan pulse reflection technique or PAUT technique.

(2) For transverse flaw testing, TOFD 45 degree inclined non-parallel scan, ultrasonic A-scan pulse reflection technique with small angle beam probe may be adopted, and parallel scan is to be carried out on the welds first depending on the weld reinforcement conditions.

2.5 Storage of documents

2.5.1 Set-up document

2.5.1.1 For document storage, documents of initial setting are to be stored separately.

2.5.2 Data documents

2.5.2.1 When storing data documents, non-detecting A-scan waveforms are to be stored. Storage of just testing images is not an acceptable form of data recording.

2.5.3 Document naming format

2.5.3.1 The document name is at least to include information such as the work number, testing position, scanning block number, plate thickness, operator, etc.

2.5.4 Storage format and requirement

2.5.4.1 Set-up documents and data documents are to be stored in a tamper-proof manner. The document name is to be unique. Testing data is to be stored for long term for information.

2.6 Data interpretation

2.6.1 Examination of data validity

2.6.1.1 The data quality is to be examined in order to ensure data validity prior to data interpretation.

2.6.1.2 The data loss, if any, is not to exceed 5% of the testing length. The data loss of adjacent scanning points is not allowed.

2.6.1.3 Coupling condition: within the scanning range, a decrease of 12 dB or above below the benchmark is not allowed for lateral wave, back-wall echo, grain noise or wave type conversion signal. Any existence of weld or structure is to be indicated in the testing records.

(1) data length: the data length is to be consistent with the scanning length, with a deviation not greater than 1% of actual scanning length or 5 mm, whichever is lesser. For segmented scanning, the adjacent data is at least to have an overlapping of 20 mm;

(2) scanning resolution: consistent with set value;

(3) display range: incomplete display of lateral wave or back-wall echo is not allowed within the testing length.

(4) the signal noise of A scan is not to be greater than 20% full screen height.

2.6.2 Classification of flaws

2.6.2.1 Flaws are classified as hazardous ones and non-hazardous ones based on the nature. Hazardous flaws mainly include cracks, lack of fusion, lack of penetration, etc. Non-hazardous flaws mainly include pores, slag inclusions, etc.

2.6.2.2 The records of flaws are to include the following contents:

(1) type of flaw (nature of flaw, e.g. surface breaking/back-wall breaking/through wall/embedded type, point like/linear/plane, etc.);

(2) position, length, depth and height (if measurable) of flaw;

(3) distribution characteristics of flaw (single point, scattered, concentrated, etc.).

2.7 Assessment of flaws and acceptance criteria

The quality of weld consists of levels 1, 2 and 3, corresponding to requirements ranging from high ones to low ones. Level 1 is applicable to important areas of ships while level 2 is applicable to areas other than important areas. Level 1 is at least to be tested by level B testing and level 2 is at least to be tested by level A testing.

Flaws are assessed in the order of hazardous flaws, single flaws, grouped flaws and cumulative flaws.

The characteristic of TOFD images and flaw measurement method are described in detail in Appendix 2. Typical images of flaws are given in Appendix 6.

2.7.1 Hazardous flaws

2.7.1.1 Hazardous flaws including crack, lack of fusion, lack of penetration, etc. are assessed as level 3.

2.7.1.2 Transverse flaws are assessed as level 3.

2.7.2 Single flaws

2.7.2.1 Non-hazardous single flaws are to be assessed in accordance with the position, height and length of flaw based on the requirements of Table 2.7.2.1.

Assessment of Single Flaws **Table 2.7.2.1**

Acceptance criteria	Thickness range of base metal (mm)	Maximum allowable length if $h < h_2$ or h_3 L_{max} (mm)	Maximum allowable height if $L \leqslant L_{max}$		Maximum allowable height if $L > L_{max}$ h_1(mm)
			Surface-breaking flaws h_3 (mm)	Embedded flaws h_2 (mm)	
Level 1	$10 < t \leqslant 15$	$0.75t$	1.5	2	1
	$15 < t \leqslant 50$	$0.75t$	2	3	1
	$50 < t \leqslant 100$	40	2.5	4	2
	$t > 100$	50	3	5	2
Level 2	$10 < t \leqslant 15$	t	2	2	1
	$15 < t \leqslant 50$	t	2	4	1
	$50 < t \leqslant 100$	50	3	5	2
	$t > 100$	60	4	6	3
Level 3	If the limits of level 2 are exceeded				

* Note: If acceptance criteria other than those specified in these Guidelines are used, they are to be approved by ISC.

2.7.3 Grouped flaws

2.7.3.1 If the distance between two individual flaws along the direction of weld length is less than the length *l* of the longer flaw and the distance along the direction of depth is less than the height h of the higher flaw, it is to be treated as single flaw and the length l_g is defined as the sum of the lengths of the individual flaws plus the distance between them. If two individual flaws overlap along the direction of length, the height (h_g) is defined as the sum of the heights of the individual flaws plus the distance between them. If two individual flaws do not overlap along the direction of length, the height (h'_g) is to be calculated in accordance with the higher flaw, see Figure 2.7.3.1.

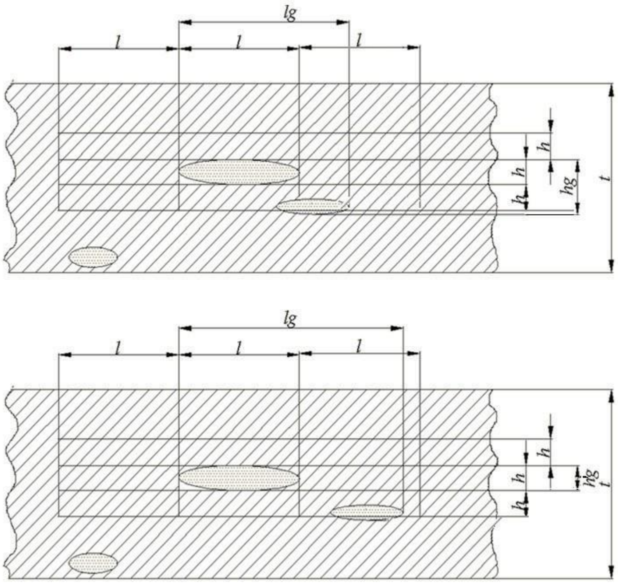


Figure 2.7.3.1 Grouped Flaws of TOFD Testing

2.7.4 Cumulative flaws

2.7.4.1 In accordance with the requirements for different acceptance levels, within the range of any 12*t*, the cumulative length of flaws is not to exceed the following value:

Level 1: 3.5*t*, maximum 150 mm;
Level 2: 4*t*, maximum 200 mm;
Level 3: If the limits above are exceeded.

2.7.4.2 For all acceptance levels, point-like flaws within any length of 150 mm are not to exceed 1.2*t*, where the unit of *t* is mm. E.g., for welds with the thickness of base metal of 20 mm, the number of point-like flaws is not to exceed 24 within any length of 150 mm.

2.7.5 Length reduction

2.7.5.1 For calculation of cumulative length or point-like flaws, if the weld length is less than 12*t* or 150 mm, the corresponding acceptance criteria are to be reduced proportionally. If the limit of cumulative length after reduction is less than the limit of single flaws, the latter is to prevail.

2.8 Reports and filing

2.8.1 Documents to be placed on file are to include setting documents (automatically generated by instruments), testing reports and initial data. All documents are to be kept for information for long term.

2.8.1.1 Testing reports are to include the following contents:

(1) Object under test, which includes the name of project, name of object under test (type, material, condition), type of weld groove, etc.

(2) Name of hardware, which includes the name and identification number of computer, the calibration validity of computer, the name and identification number of probes, the name of wedges, the identification number of encoders, the name and identification number of blocks, etc.

(3) Parameter setting, which includes reference standards, testing level, probe frequency, size of probe element, wedge angle, PCS value, resolution of encoder, average time, position of the probe in relation to the weld, verification data of block, value of size of top surface dead zone, etc.

(4) Testing content, which includes name of setting, testing type, testing time, surface condition, couplant, testing temperature, scan increment, testing position and numbering method, testing direction, etc.

(5) Assessment of flaws, which includes the name and edition of data interpretation software in use, reference standards, acceptance levels, data processing function in use, type or characteristics of flaw, position of flaw in the weld length direction, length of flaw, depth of flaw, height of flaw, whether satisfactory or not, diagram of flaw exceeding standards, scanning images, etc.

(6) Information of relevant personnel

Name, signature, level of data acquisition personnel and date; name, signature, level of data interpretation personnel and date; name, signature, level of report review personnel and date.

CHAPTER 3 PAUT TECHNIQUE

This Chapter gives the method of testing and assessment of flaws using PAUT technique and specifies basic requirements for testing system, design of procedures, calibration, on-site data acquisition, data interpretation, testing report, etc.

PAUT consists of two methods, i.e. manual and semi-automatic/automatic ones. Instead of carrying out encoding and data acquisition, the manual method mainly uses zigzag scan which is similar to type A pulse reflection ultrasonic waves. Semi-automatic/automatic method carries out encoding and data acquisition instead of encircling, cornering and front-back auxiliary scans, unable to detect transverse flaws. The difference between semi-automatic and automatic method is that the former is a manually-driven scan and the latter is an automatic scan driven by the electric motor.

PAUT technique using semi-automatic/automatic method is mainly discussed in these Guidelines.

3.1 Testing system

PAUT testing system includes ultrasonic instruments, software, probes/wedges, scanning mechanisms, blocks and other accessories. Reference is made to Figure 2.1. The above system is to be furnished with a product quality certificate or a quality document issued by the manufacturer and the ultrasonic instrument is to be within the valid calibration period.

In addition to complying with the requirements of this Chapter, PAUT testing system is also to satisfy the relevant requirements of JB/T10061 and CB/T3559.

3.1.1 Ultrasonic instruments

3.1.1.1 The pulser is to satisfy the following requirements:

(1) For transmitted pulse, reference is made to the requirements of 2.1.1.1(1) and (2).

(2) The repetitive frequency of pulse is to be adjustable with a maximum value not less than 2 KHz.

(3) The voltage of transmitted pulse of all excitation channels is to be consistent. The maximum offset value is not to be greater than 5% of the setting value.

(4) The interference between adjacent channels is not to be greater than -30 dB.

(5) The delay accuracy of transmitted pulse of each channel is not to be greater than 5 ns.

3.1.1.2 For the requirements for the signal receiver, reference is made to the requirements of 2.1.1.2(1) and (2).

3.1.1.3 Digitization is to satisfy the following requirements:

(1) The digital sampling frequency of signal ⩾ 8 times the nominal frequency of probe.

(2) For sampling digit, encoding display of signal amplitude, delay and window range of A scan signal and external trigger, reference is made to the requirements of 2.1.1.3(1) and (2).

3.1.1.4 The software in use is to have the following functions:

(1) The software is to have functions of simulation, import or setting calculation of the focal law.

(2) The software is at least to have A, B, C, D, S and E views or imaging mode.

(3) The instrument is to have the function of gain compensation, capable of ACG and TCG/DAC calibration.

(4) The video smoothing function is recommended.

(5) The raw data in storage is to be capable of being replicated without being changed.

3.1.2 Probes

3.1.2.1 The use of probes is to comply with the following requirements:

(1) The number of elements in common one-dimensional linear array probes is in general not to be less than 8 while that in probes of special design (e.g. annular, sectorial area array probes) is not restricted.

(2) The deviation of the measured value relative to the nominal value of probe central frequency is not to be greater than 10%. -6dB relative bandwidth is not to be less than 60%.

(3) Within the angle of deflection in use, the theoretical beam of array element cycle is not to generate grating lobe.

(4) The consistency of central frequency, bandwidth and sensitivity of each array element is not to be greater than 5% of average value.

(5) The interference between adjacent elements is not to be greater than -30 dB.

(6) For elements using single focal law, the number of damaged elements is not allowed to be greater than 10% of total number of elements in use and any adjacent element is not allowed to be damaged.

3.1.3 Wedges

3.1.3.1 For testing of oblique incidence, tapered wedges are in general to be used to satisfy the requirements for beam deflection.

3.1.3.2 A sound absorption area is to be designed at the fore end of wedge in order to prevent the transmitted signal from forming multiple echoes in the wedge.

3.1.3.3 If the tested surface is curved, the wedge used is to satisfy the requirements of 2.1.3.5.

3.1.4 Blocks

3.1.4.1 Blocks used by PAUT technique include standard blocks, reference blocks and simulation blocks.

3.1.4.2 The materials of blocks are to satisfy the requirements of 2.1.4.2.

3.1.4.3 If the tested surface is curved, blocks are to satisfy the requirements of 2.1.4.4.

3.1.4.4 For specific design of blocks, reference is made to Appendix 3.

3.1.5 Scanning mechanisms and encoders

3.1.5.1 Scanning mechanisms are to be such that the probe moves steadily along the pre-determined scanning path.

3.1.5.2 For semi-automatic or automatic testing, it is to be ensured that the probe is moved in synchronization with the encoder count.

3.1.5.3 For automatic testing, the encoding signal is to satisfy the requirements of subparagraph c of 5.1.5.

3.2 Design of testing procedures

3.2.1 Testing specifications

3.2.1.1 PAUT testing specifications mainly include the following contents:

(1) determination of testing purpose (testing task, testing position, reference standards, testing level, acceptance level etc.);

(2) determination of product scope (shape, type, material quality, wall thickness, welding procedures of the test object, etc.);

(3) design of procedures (type of computer, probes/wedges, scanning mechanisms, blocks, focal law, scanning path, additional testing of transverse flaws, etc.);

(4) parameter setting and calibration;

(5) verification of procedures;

(6) testing preparation;

(7) scanning and data acquisition;

(8) data analysis and interpretation;

(9) assessment of flaws and quality classification.

3.2.2 Testing levels

3.2.2.1 Testing levels of PAUT technique consist of levels A, B, C and D ranging from low one to high one. Detailed requirements are given in Table 3.2.2.1.

3.2.2.2 For all testing levels, the full coverage of the testing area by beams is to be achieved.

3.2.2.3 If the requirements of relevant levels cannot be satisfied due to the restriction of objective conditions, special testing procedures are to be developed in accordance with the requirements of level D and submitted to ISC for approval.

Requirements of Different Testing Levels Table 3.2.2.1

Testing level	Thickness of base metal /mm	Weld type	Testing position	Scan type	Transverse flaws
Level A	≤50	Butt weld	One surface and one side	S-Scan or E-Scan	If necessary
		Fillet weld T weld	One surface and one side	S-Scan or E-Scan	If necessary
Level B	≤100	Butt weld	One surface and two sides One surface and one side	S-Scan or E-Scan S-Scan and E-Scan	If necessary
		Fillet weld T weld	One surface and one side	S-Scan and E-Scan	If necessary
	＞100	Butt weld	Two surfaces and two sides	S-Scan or E-Scan	If necessary
		Fillet weld T weld	One surface and two sides	S-Scan and E-Scan	If necessary
Level C	≤100	Butt weld	One surface and two sides	S-Scan and E-Scan	Must be tested
		Fillet weld T weld	One surface of web and outer side of face plate	S-Scan and E-Scan，	Must be tested
	＞100	Butt weld	Two surfaces and two sides	S-Scan和E-Scan	Must be tested
		Fillet weld T weld	Two surfaces of web and outer side of face plate	S-Scan和E-Scan	Must be tested
Level D	Special testing procedures				
Note 1: E-Scan means testing by means of linear scanning beams of two different angles. Note 2: For fillet weld and T weld in level C, testing of transverse flaws may be carried out an oblique scan of a small angle at the weld side of web, or a parallel scan above the weld of web or face plate.					

3.2.3 Testing area

3.2.3.1 The height of testing area is the thickness of the test object.

3.2.3.2 The width of testing area is the width of weld plus areas of 10 mm on both sides of the weld or the heat affected zone (whichever is greater).

3.2.3.3 For re-testing or accurate quantification of flaws, the testing area may be reduced appropriately.

3.2.3.4 The testing area is to be shown in the form of diagram in the testing report.

3.2.4 Probes

3.2.4.1 The probe frequency is to be selected in accordance with the requirements of Table 3.2.4.1.

Probe Frequency **Table 3.2.4.1**

Plate thickness (mm)	Frequency (MHz)
$6 \leq T < 10$	10
$10 \leq T < 50$	5～10
$T \geq 50$	2～5

3.2.4.2 For testing of weld, one-dimensional linear array probes are in general used.

3.2.4.3 The size and number of elements is to be selected in accordance with the following requirements:

(1) The selection of elements with greater size may lead to higher testing sensitivity and greater depth of focus, but the size of elements is not to be too large in order to avoid large array element cycle giving rise to grating lobe. In general the array element cycle is to be less than half wave length.

(2) The number of elements is to satisfy the requirements for the size of probe excitation aperture and the scan coverage in E-scan. The number of elements corresponding to the size of probe excitation aperture is not to exceed the number of excitation channel of selected equipment.

3.2.5 Wedges

3.2.5.1 Typical phased array wedges include 0°, 45°, 55°, 60°etc. The selected wedge angle is to correspond with the beam angle of E-scan or the intermediate value of deflection angle range of S-scan insofar as practicable.

3.2.6 Design of focal law

3.2.6.1 The coverage of testing beams is to satisfy the following requirements:

(1) CAD drawing or relevant NDT simulation software is in general used to design the coverage of testing beams. It is to be ensured that designed testing beams can fully cover the testing area of welds. Where such requirement cannot be satisfied, auxiliary scanning or other testing method is to be added.

(2) When level B and level C testing are used, the overlapping area between different scanning settings is to be large insofar as practicable.

(3) Settings of special testing channels with regard to specific position or flaw are added as necessary.

(4) In general, the number of elements in a single excitation is not to be less than 8.

3.2.6.2 The deflection range of S-Scan is to satisfy the following requirements:

The beam deflection capacity of probes is to be tested and verified during the design of procedures. For the design of focal law, only the range of beam angles that have been verified is allowed. In general, the range of deflection angle of transverse wave S-Scan is recommended to be 40º～75º .

Note: With the increase of the deflection angle of S-Scan, the beam resolution decreases and the angle error increases.

3.2.6.3 The following factors are mainly considered during the selection of depth of focus:

(1) The depth of focus is in general to be set as 2 times the plate thickness of the object. Where attention is given to flaws with a relatively short sound path, the probe aperture used is not to be too large.

(2) The phased array technique can only realize focus in the near field region of probe. Where the focus testing is required for flaws with specific depth, the depth of focus may be set in way of the depth of the flaw, which may lead to rapid decrease of testing sensitivity at other positions.

(3) Where it is practicable, Dynamic Depth Focusing (DDF) is recommended to improve the beam resolution.

3.2.6.4 The setting of coupling monitoring channels is recommended to monitor the coupling condition of probe/wedges on the surface of the object.

3.3 Parameter settings

3.3.1 Focal law

3.3.1.1 The focal law is to be correctly set up in accordance with pre-determined testing parameters. Where several sets of focal laws are used, the information on element number and serial number, beam deflection angle and focus position is to be set up for each set.

The effect of probe excitation aperture and depth of focus on imaging results of S-Scan is described in detail in Appendix 5.

3.3.2 Pulsers and signal receivers

3.3.2.1 The use of pulsers and signal receivers is to comply with the following requirements:

(1) excitation voltage: in accordance with relevant requirements of 2.3.2.1;

(2) pulse width: the pulse width is to be adjusted in accordance with probe frequency, testing sensitivity and noise-signal ratio;

(3) filtering: in accordance with relevant requirements of 2.3.2.1;

(4) The video smoothing function is recommended to improve the quality of scanning images.

3.3.3 Selection of views of display range

3.3.3.1 The setting of display range is to be such that the testing area of weld is covered by it and excessive ineffective scan areas are removed, see Figure 3.3.3.1. The view combinations of A-S-B or A-E-B are recommended.

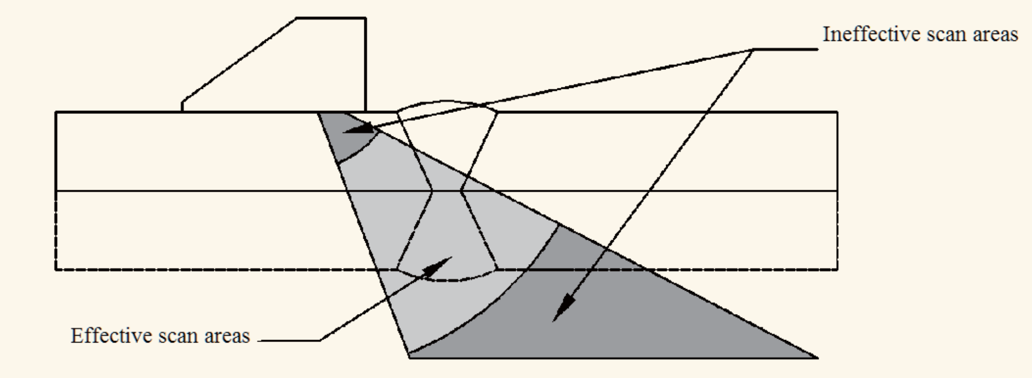


Figure 3.3.3.1 Display Range

3.3.4 Sensitivity settings

3.3.4.1 Sensitivity settings are to be adjusted on the reference block. Specific processes are given in Appendix 4.

3.3.5 Digitization

3.3.5.1 Sampling frequency and digit are to satisfy the requirements of 2.2.6.3(1) and (2).

3.3.5.2 For phased array testing, the double-wave detection signal is to be used.

3.3.6 Scanning settings

3.3.6.1 Relevant scanning increment or resolution is set up in accordance with the plate thickness range of the object. Specific values are given in Table 3.3.6.1.

Scanning Resolution **Table 3.3.6.1**

Plate thickness t/mm	Maximum scanning increment/mm
$t < 10$mm	1.0
$10 \leq t < 150$	2.0
$t \geq 150$	3.0

3.4 Calibration

The calibration of PAUT technique includes the sound velocity of materials under test, wedge delay, calibration of sensitivity and encoder for the purpose of obtaining more accurate testing results. Detailed calibration processes and steps are given in Appendix 4.

3.4.1 Examination of elements

3.4.1.1 Prior to calibration, elements intended to be used by the probe are to be examined. A typical scanning image of element examination is shown in Figure 3.4.1.1.

3.4.1.2 For the used elements, the number of damaged elements is not to be greater than 10% of total number of elements in use and any adjacent element is not allowed to be damaged.

3.4.1.3 The sensitivity deviation of elements in use is not to be greater than 6 dB and the sensitivity deviation between adjacent elements is not to be greater than 3 dB. Any element with deviation more than 6 dB is to be treated as damaged element for statistical purpose.

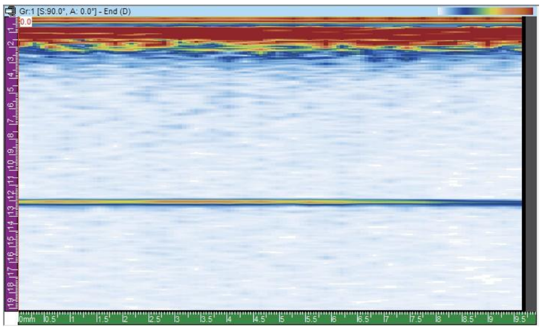


Figure 3.4.1.1   Scanning Image of Element Examination

3.4.2 Calibration of sound velocity and wedge delay

3.4.2.1 After calibration of sound velocity and wedge delay, the error of depth and horizontal positioning accuracy on the 3 mm side drilled hole is not to be greater than 1 mm.

3.4.3 Calibration of encoders

3.4.3.1 Calibration of encoders is to be carried out by referring to 2.3.3.

3.4.4 Calibration of sensitivity and TCG

3.4.4.1 After calibration of sensitivity and TCG of phased array, the consistency deviation of each beam is not to be greater than ±5% full screen height.

3.4.5 Examination of system display

3.4.5.1 The examination of system display is to satisfy the following requirements:

(1) The examination of system display is to be carried out after the calibration of equipment.

(2) The examination of system display is to be carried out on the block.

(3) The deviation with regard to the depth and horizontal position of the standard reflector on the block is not to be greater than 1 mm. The deviation of signal amplitude is not to be greater than 5%.

(4) For S-Scan, beams with minimum, intermediate and maximum angles are to be examined.

(5) For E-Scan, two edge beams are to be examined.

(6) The number of examination points for each beam is not to be less than 2. In general, middle and far points within the display range are selected.

3.5 On-site data acquisition

3.5.1 Surface condition

3.5.1.1 Specific requirements for the surface condition during data acquisition are to be defined by referring to 2.4.1.1.

3.5.2 Marking of testing position and testing direction

3.5.2.1 Specific requirements for marking of testing position and testing direction are to be defined by referring to 2.4.2.

3.5.3 Testing of base metal

3.5.3.1 Prior to level C testing, vertical beam testing is to be carried out to the base metal on both sides of the weld where the beam may pass through. Any flaw in the base metal which may affect the transmission of acoustic energy is to be recorded.

3.5.3.2 During testing of base metal, back wall echo of the object is to occur twice as a minimum. The second echo in way of position without flaw is set as 100% full screen height to test sensitivity.

3.5.3.3 For areas where the flaw signal amplitude is more than 20% or where the echo disappears, the surface of the object is to be marked and recorded.

3.5.4 Couplant

3.5.4.1 Relevant requirements for couplant in use are to be defined by referring to 2.4.4.1.

3.5.5 Temperature

3.5.5.1 Relevant requirements for temperature during data acquisition are to be defined by referring to 2.4.5.

3.5.6 Scan and data acquisition

3.5.6.1 Relevant requirements for the scanning speed are to be defined by referring to 2.4.6.1.

3.5.6.2 Relevant requirements for the scanning coverage are to be defined by referring to 2.4.6.2.

3.5.6.3 During scanning, it is to be ensured that the horizontal deviation of the actual scanning path relative to the intended scanning path is not greater than 2 mm.

3.5.6.4 Re-scanning is to be carried out in the following cases:

(1) where the data quality is unsatisfactory, see 3.8 for detailed requirements.

(2) where the deviation of the scanning length relative to the actual length exceeds 1% of the scanning length or 5 mm, whichever is lesser;

(3) the scanning offset exceeds the requirements of 6.5.6.3.

3.5.6.5 Relevant requirements for the checking of testing system are to be defined by referring to 2.4.6.5.

3.6 Storage of documents

See 2.5.

3.7 Data interpretation

3.7.1 Examination of data validity

3.7.1.1 The data quality is to be examined in order to ensure data validity prior to data interpretation.

3.7.1.2 The data loss is not to exceed 5% of the testing length. The data loss of adjacent scanning points is not allowed.

3.7.1.3 There is to be neither sudden disappearance of the noise signal within the scanning range nor abnormal signal from the coupling monitoring channel. Any existence of wedge fixed wave, transverse weld or other structure is to be indicated in the testing records.

3.7.1.4 The data length is to be consistent with the scanning length. For segmented scanning, the adjacent segment is at least to have an overlapping of 20 mm.

3.7.1.5 The scanning increment is to comply with set value.

3.7.1.6 The display range is to include the testing area.

3.7.1.7 The signal noise of A scan is not to be greater than 20% full screen height.

3.7.2 Classification of flaws and records

3.7.2.1 Flaws are to be identified in accordance with the following requirements:

(1) The structural signals (non-relevant indications) and flaw signals (relevant indications) are identified in accordance with the structural characteristics of welds or by referring to simulated images.

(2) The nature of flaws is in general to be judged in connection with specific welding procedures, position of flaws and characteristics of signal images.

Typical images of flaws are given in Appendix 6.

3.7.2.2 Flaws are classified as hazardous ones and non-hazardous ones based on different levels of hazard.

Hazardous flaws mainly include cracks, lack of fusion, lack of penetration, etc. Non-hazardous flaws mainly include pores, slag inclusions, etc.

3.7.2.3 The records of flaws are to include the following contents:

(1) type of flaw (nature of flaw, e.g. surface breaking/back-wall breaking/through wall/embedded type, point like/linear/plane, etc.);

(2) position, length and depth of flaw;

(3) distribution characteristics of flaw (single point, scattered, concentrated, etc.).

3.7.2.4 The positioning of flaws is to include the following contents:

(1) position of flaw: the start point of scan direction;

(2) depth of flaw: the minimum depth measured from the scanning surface;

(3) horizontal position: the horizontal distance from the centerline of weld to the minimum depth of flaw.

3.7.2.5 The quantification of flaws is to include the following contents:

(1) echo amplitude: the maximum echo amplitude of flaws. In case of signal saturation of A scan, it is to be truthfully recorded;

(2) length of flaw: the length of flaw is to be measured by -6 dB method. For an indication of flaw with single wave peak, the length is measured by means of the peak value minus 6 dB. For an indication of flaw with several wave peaks, the length is measured by means of the tip peak value minus 6 dB. Saturated A scan signal may be dealt with in accordance with 100% full screen height.

3.8 Quality level and acceptance criteria

3.8.1 All hazardous flaws, e.g. cracks, lack of fusion, lack of penetration, etc., are assessed as non-conformity.

3.8.2 All transverse flaws are assessed as non-conformity.

3.8.3 Quality classification of single flaws

For PAUT testing, echo with wave amplitude exceeding Φ3-14dB is to be analyzed. All flaws with wave amplitude exceeding the recording level are to be recorded and classified in accordance with the requirements of Table 3.8.3.

Quality Classification of PAUT Testing Table 3.8.3

Acceptance level	Quality level in ISO 5817	Quality level in ISO11666	Wave height of flaws	Length of flaws	Recording level
Level 1	Level B	Level 2	Φ3-4dB~Φ3	Not greater than 0.5t or 20 mm (whichever is lesser)	Φ3-4dB
			Φ3-10dB~Φ3-6dB	Not greater than t or 20 mm (whichever is lesser)	Φ3-10dB
			Φ3-14dB~Φ3-10dB	Not greater than 2.5t or 20 mm (whichever is lesser)	Φ3-14dB
Level 2	Level C	Level 3	Φ3~Φ3+4dB	Not greater than 0.5t or 30 mm (whichever is lesser)	Φ3
			Φ3-6dB~Φ3-2dB	Not greater than t or 30 mm (whichever is lesser)	Φ3-6dB
			Φ3-10dB~Φ3-6dB	Not greater than 2.5t or 30 mm (whichever is lesser)	Φ3-10dB
Level 3	If the limits above are exceeded				

* Note: If acceptance criteria other than those specified in these Guidelines are used, they are to be approved by ISC.

3.8.4 Grouped flaws

For PAUT testing, if the distance d_x between two individual flaws along the direction of scanning is less than 2 times the length l_1 of the longer flaw and the distances between projections of two flaws at the horizontal and depth directions are both less than 10 mm, it is to be treated as single flaw and the length l_{12} is defined as the sum of the lengths of the individual flaws plus the distance between them, see Figure 3.8.4.

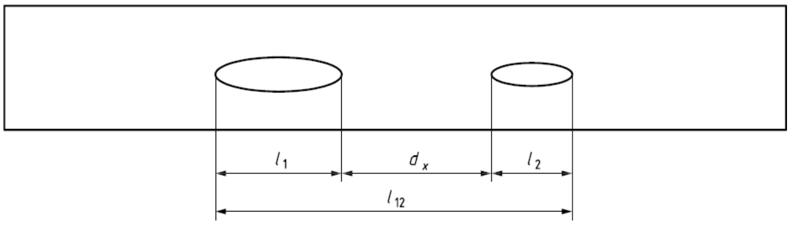


Figure 3.8.4 Grouped Flaws of PAUT Testing

3.8.5 Cumulative length of flaws

For PAUT testing, with regard to flaws with wave amplitude exceeding the recording level, the cumulative length of flaws is to be calculated. Within the range of any 100 mm, the cumulative length of flaws is to be subject to quality classification in accordance with the requirements of Table 3.8.5.

Level of Cumulative Length of Flaws of PAUT Table 3.8.5

Acceptance level	Quality level in ISO5817	Quality level in ISO11666	Acceptance requirements for cumulative flaws
Level 1	Level B	2	20mm
Level 2	Level C	3	30mm
Level 3	If the limits above are exceeded		

3.8.6 Point-like flaws

For all acceptance levels, the number of point-like flaws within any length of 150 mm is not to exceed 1.2*t*, where the unit of *t* is mm. E.g., for welds with the thickness of base metal of 50 mm, the number of point-like flaws is not to exceed 60 within any length of 150 mm.

3.8.7 Length reduction

For calculation of cumulative length or point-like flaws, if the weld length is less than 12*t* or 150 mm, the corresponding acceptance criteria are to be reduced proportionally. If the limit of cumulative length after reduction is less than the limit of single flaws, the latter is to prevail.

3.9 Reports and filing (records, reports and files)

3.9.1 The object under test is at least to include the following contents:

(1) name of project;

(2) name of object under test, type, material, condition;

(3) type of weld groove.

3.9.2 The name of hardware is at least to include the following contents:

(1) name and identification number of computer;

(2) name and identification number of probes;

(3) identification number of encoders;

(4) name and identification number of blocks.

3.9.3 Parameter setting is to include the following contents:

(1) reference standards;

(2) testing level;

(3) sensitivity setting method;

(4) probe frequency;

(5) probe aperture;

(6) wedge angle;

(7) scanning type;

(8) range of angle;

(9) position of the probe in relation to the weld;

(10) diagram of wave beam coverage;

(11) resolution of encoder;

(12) verification data of block.

3.9.4 The testing report is to include the following contents:

(1) name of setting;

(2) testing type;

(3) testing time;

(4) surface condition;

(5) couplant;

(6) testing temperature;

(7) scan increment;

(8) testing position and numbering method;

(9) testing direction;

(10) name, signature, level of testing personnel and testing date.

3.9.5 The report on flaw assessment is to include the following contents:

(1) name and edition of data interpretation software in use;

(2) reference standards;

(3) acceptance level;

(4) data processing function in use;

(5) position of flaw, distance between the flaw and the weld centerline, length and depth of flaw;

(6) whether satisfactory or not;

(7) scanning image of flaw exceeding standards;

(8) name, signature, level of data interpretation personnel, date;

(9) name, signature, level of report review personnel, date.

Appendix 1 Technical Limitations of TOFD

A1.1 TOFD technique is sensitive to the nature of materials

TOFD diffraction signals are weak with relatively high gains. This amplifies the grain noise in welds and base metals and lowers the testing signal-to-noise ratio, which makes it difficult for flaw identification. At present TOFD technique is applied to the testing of carbon steel and other fine grain materials and is not applicable to coarse grain materials such as cast steel and stainless steel.

A1.2 Testing objects are unitary, and such technique is only applicable to plate or pipe butt welds.

The symmetrical arrangement of two transmitting-receiving probes required by TOFD technique makes it difficult to test transition welds, fillet welds, T-shape welds and tubular joint welds. The positioning and quantitative errors are increased in testing transition welds of. Fillet welds and T-shape welds require special testing procedures because probes cannot be placed in the same plane. With a lot of limitations, this procedure is less adopted now.

A1.3 Single-time scanning cannot determine the exact position, depth and height of flaws.

The testing and positioning of flaws by TOFD relies on the arrival time of signals. The time difference between the internal diffraction signals and lateral waves is computed by the triangular geometry to linearize the depth coordinate. In theory, flaw echo is located on the ellipse with the focal points formed from the transmitting/receiving beams' principal axis, as is shown in Figure A1. In single scanning, flaws are usually presumed to be located on the centre line of welds to calculate the depth and height of flaws. Therefore, there would be errors for flaws deviating from the centre line of welds, as is shown in Figure A1. The larger the deviation is, the bigger the errors will be.

A1.4 The existence of dead zones in top and bottom surfaces

Lateral waves have a certain continuous breadth. For flaws located on the near-surface, since its transit time is close to the transit time of lateral waves, its diffraction waves will be submerged by lateral waves, leading to the failure in flaw detection. This dead zone is named the dead zone in the top surface. In testing flaws near the back wall and on both sides of the centre line of welds, the transit time of diffraction waves may be longer than the arrival time of back wall echo. In this way, the diffraction signals of flaws are submerged by back wall echo, leading to the failure in flaw detection. This dead zone is named the dead zone in the bottom surface as is shown in Figure 2.1. The dead zone in the top surface is to be supplemented with other testing techniques, such as the conventional ultrasound, PAUT, and magnetic particle. The depth of effective testing is to be confirmed before the use of surface testing methods. Since the bottom surface dead zone of TOFD is relatively small, offset non-parallel scan is to be additionally used when the testing level is relatively high. When the testing level is low, it can be neglected.

A1.5 Hard to test transverse flaws

When testing transverse flaws by TOFD, the signals will be shown as tiny arcs. It is hard to differentiate the transverse flaws because they are mixed with the signal of other flaws (if any) in the welds.

A1.6 The overlapping of flaw signals on both sides of the centre line of welds will result in failure in the positioning in the horizontal direction.

Only when the standard non-parallel scanning is adopted, all the flaw indications in the welds will overlay and be displayed in the same B-Scan image. For example, flaw 1 and 2 in the same ellipse in Figure A1 will overlay in the same position in B-Scan, which is hard to differentiate.

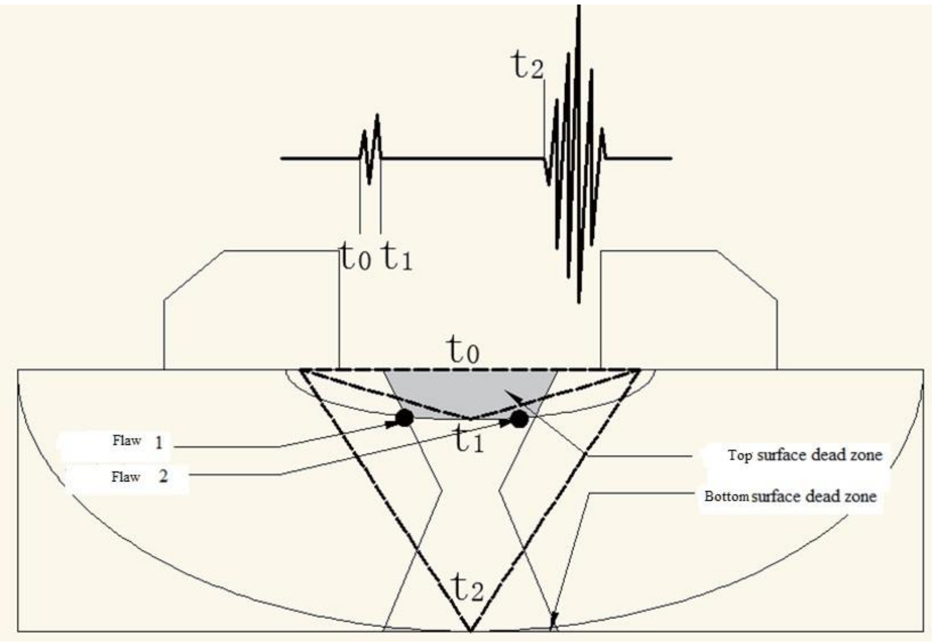


Figure A1 Testing Principle of TOFD and Diagram of Dead Zone

Appendix 2 Basic Features of TOFD Images and Measuring Methods of Flaws

A2.1 Data quality

A2.1.1 Excessively high or low gains

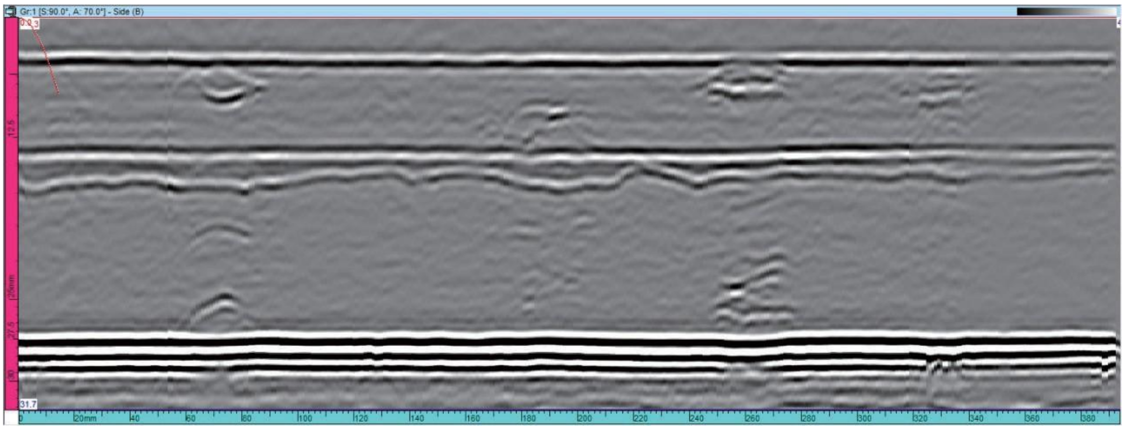


Figure A2.1 B-Scan Image of TOFD Testing (Proper Gains)

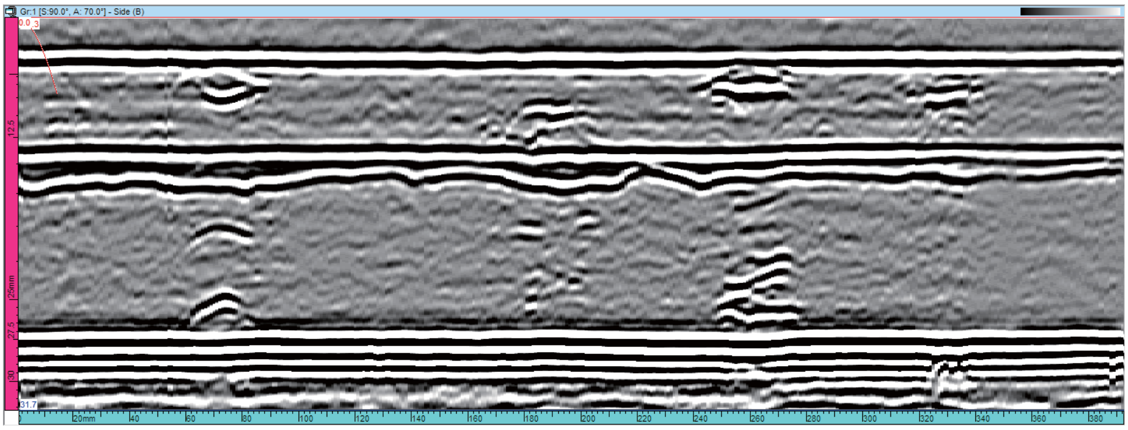


Figure A2.2 B-Scan Image of TOFD Testing (Excessively High Gains)

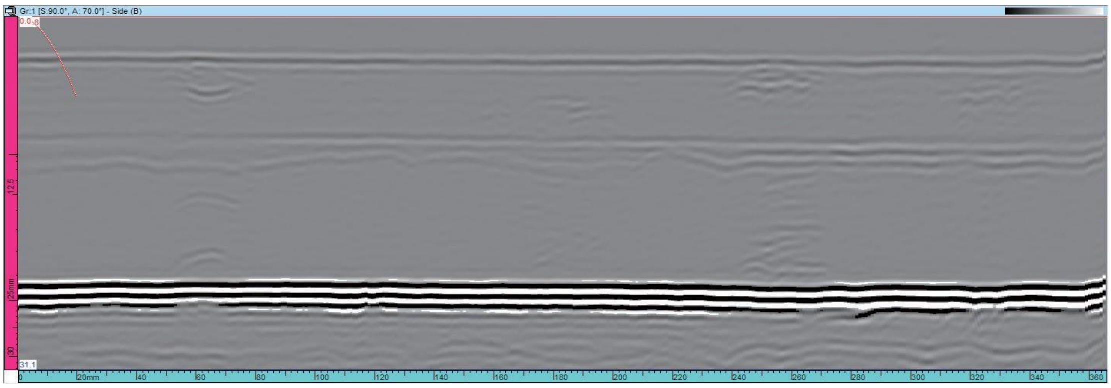


Figure A2.3 B-Scan Image of TOFD Testing (Excessively Low Gains)

A2.1.2 Improper display range

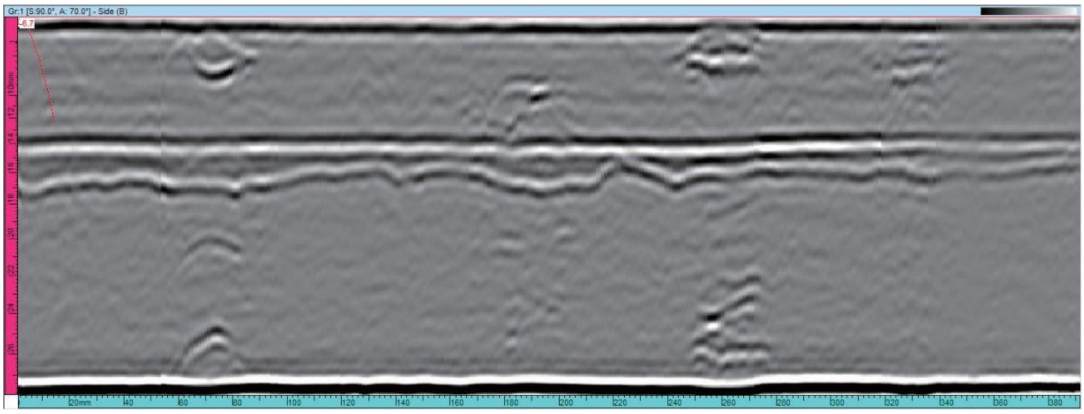


Figure A2.4 Improper Settings of Display Range
(Incomplete Lateral Waves and Conversion Waves)

A2.1.3 Abnormal synchronization of time base

Figure A2.5 Abnormal Synchronization of Time Base

A2.1.4 Data loss and poor coupling

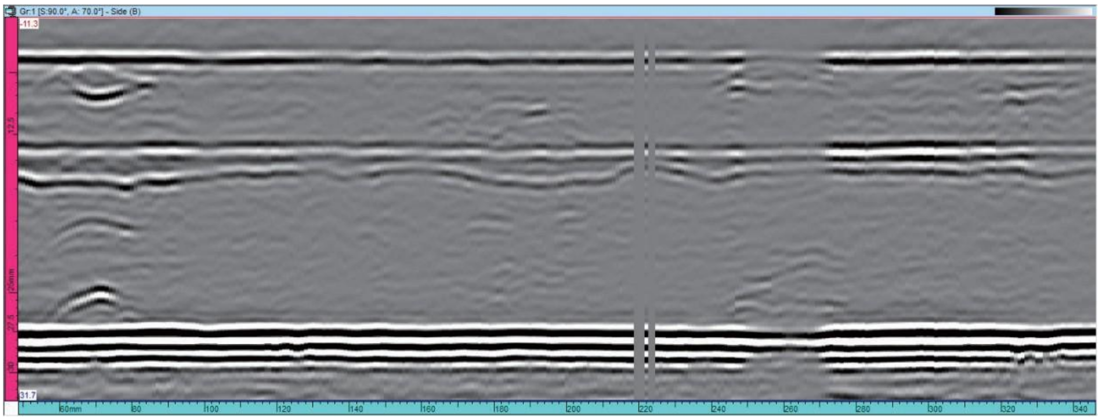


Figure A2.6 Data Loss and Poor Coupling

A2.1.5 Variation in the thickness of the coupling layer

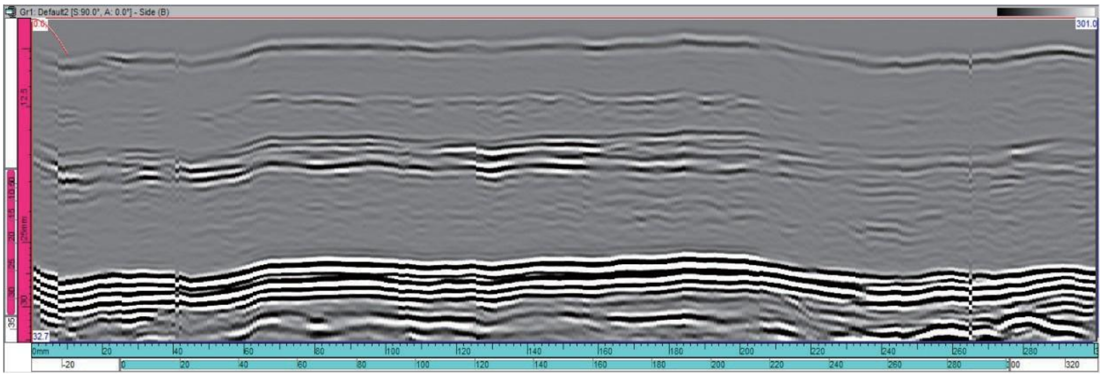
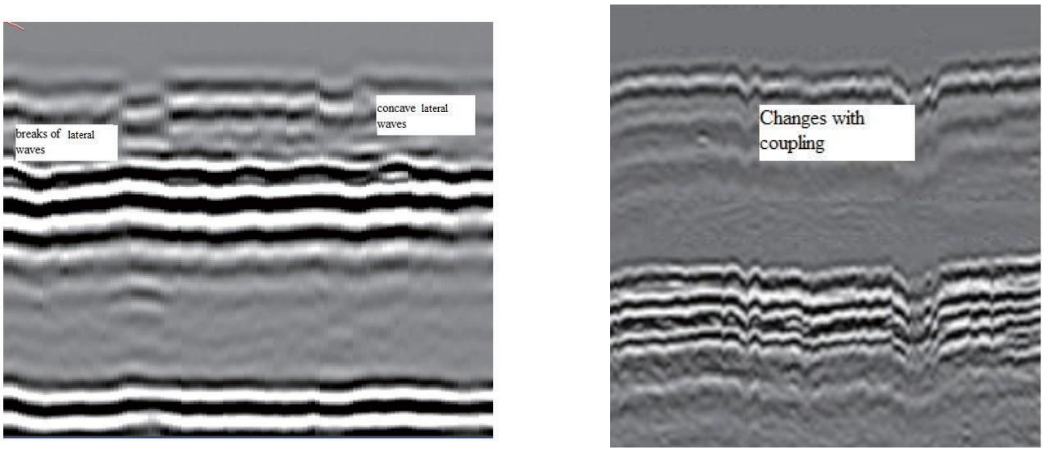


Figure A2.7 Changes of the Thickness of the Coupling Layer Resulting in Fluctuations of Lateral Waves

A2.2 Basic features of flaws in TOFD images

A2.2.1 Scanning-surface-breaking flaws

Large scanning-surface-breaking flaws will result in obvious breaks of lateral waves, where lower-tip signals of flaws occur with the same phase and time lag. Smaller scanning-surface-breaking flaws may also result in concave lateral waves. But distinctions are to be made between the scanning-surface-breaking flaws and the image features of partial poor coupling. The former will not result in changes of the back wall echoes while the latter will result in ups and downs of signals in the same position.



(a) (b)

Figure A2.8 Scanning-Surface-Breaking Flaw (a) and Changes of Coupling (b)

A2.2.2 Back-wall-breaking flaws

Large back-wall-breaking flaws will break the back wall echo and result in an upper-point signal of flaws with a phase opposite to lateral waves and earlier than the back wall echo. Back-wall-breaking flaws usually will not break the back wall echo, but will reduce or disturb them or result in an upper-point diffraction signal of flaws.

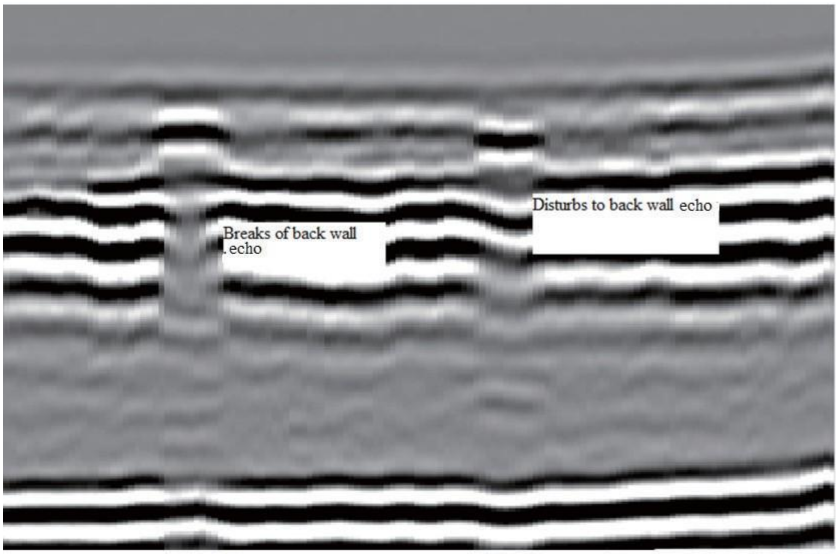
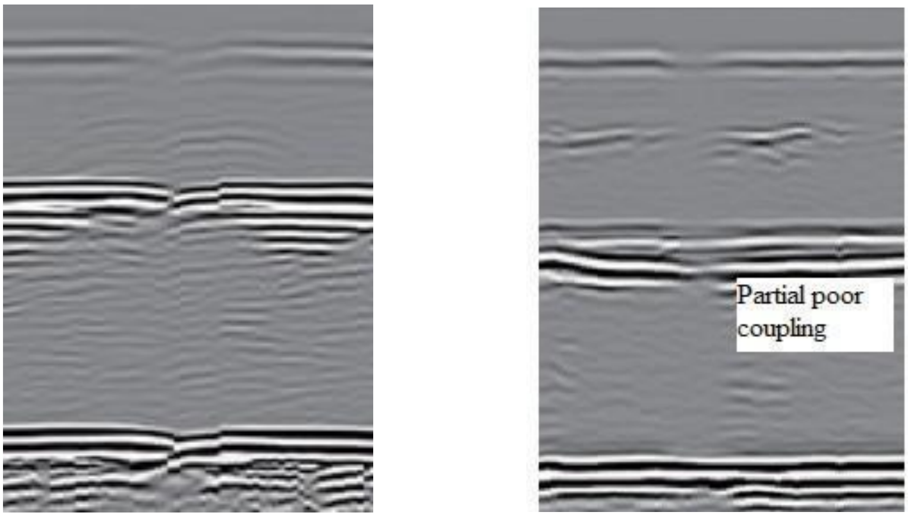


Figure A2.9 Back-Wall-Breaking Flaws

A2.2.3 Through-wall flaws (openings on both sides)

Through-wall flaws mainly feature the reduction or elimination of lateral waves and back wall echoes at the same time and sometimes many diffraction signals with depth. Distinctions are to be made to the image features between through-wall flaws and partial poor coupling.



(a) (b)

Figure A2.10 Through-wall Flaw (a) and Partial Poor Coupling (b)

A2.2.4 Embedded flaws

Embedded flaws usually won’t affect lateral waves and back wall echoes and can be divided into four types according to the display features:

1) Point-like flaw

Displayed as: hyperbola arcs without measurable length and height

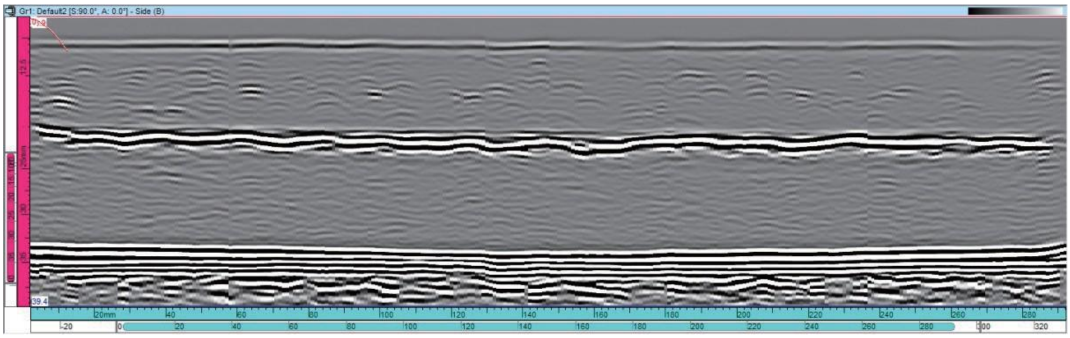


Figure A2.11 Point-Like Flaw

2) Elongated flaw with no measurable height

Displayed as: a certain length without a measurable height

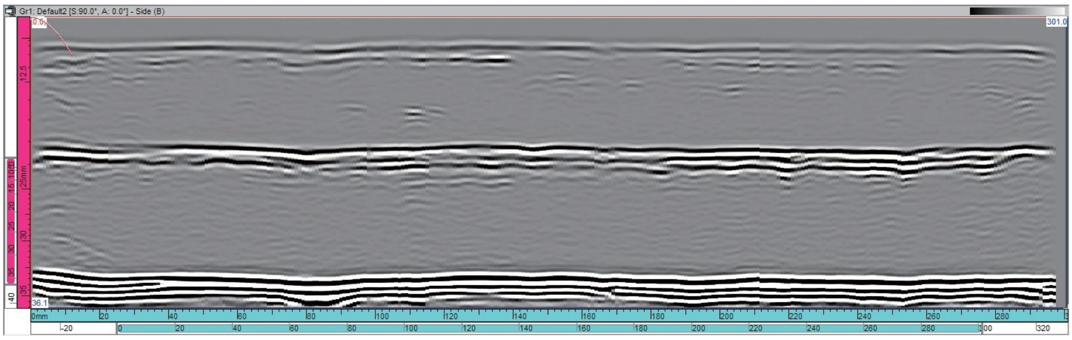


Figure A2.12 Elongated Flaw with No Measurable Height

3) Elongated flaws with a measurable height

Displayed as: a certain length with upper and lower-tip signals of opposite phases. The phase features of upper and lower-tip signals and their positions can be used to measure their height.

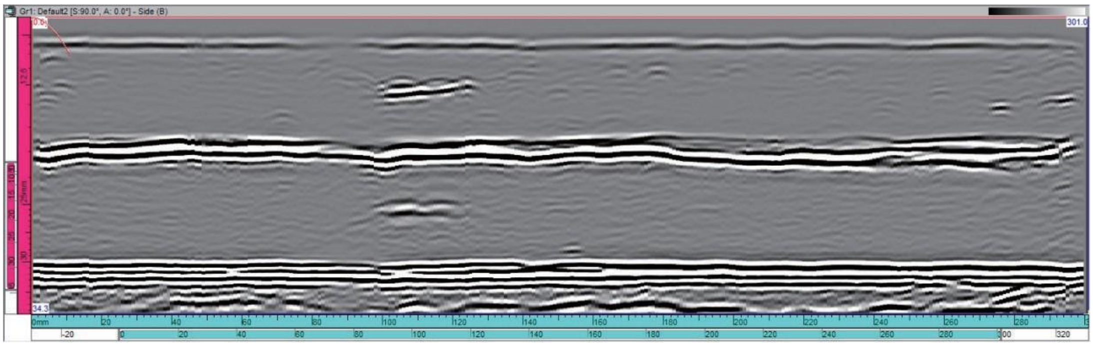


Figure A2.13 Elongated Flaws with a Measurable Height

A2.3 Measurement of flaws

A2.3.1 Length measurement of flaws

The fitting method of hyperbolic pointer is to be adopted for the length measurement of flaws. For flaws with an excessively long arc, the fitting method of hyperbolic pointer is to start with the 1/3 position from the end of the arc.

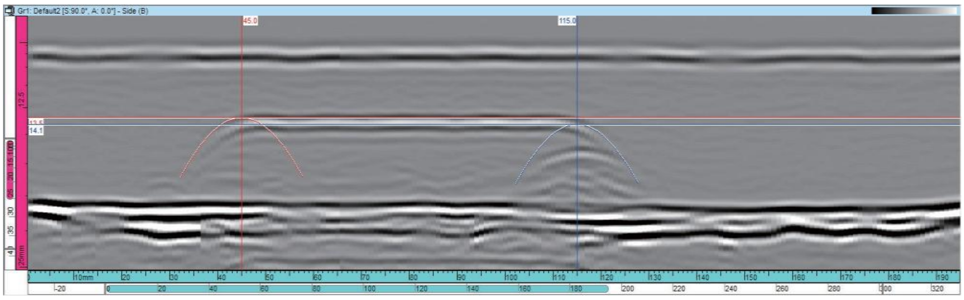


Figure A2.14 Use of the Fitting Method of Hyperbolic Pointer in the Length Measurement of Flaws

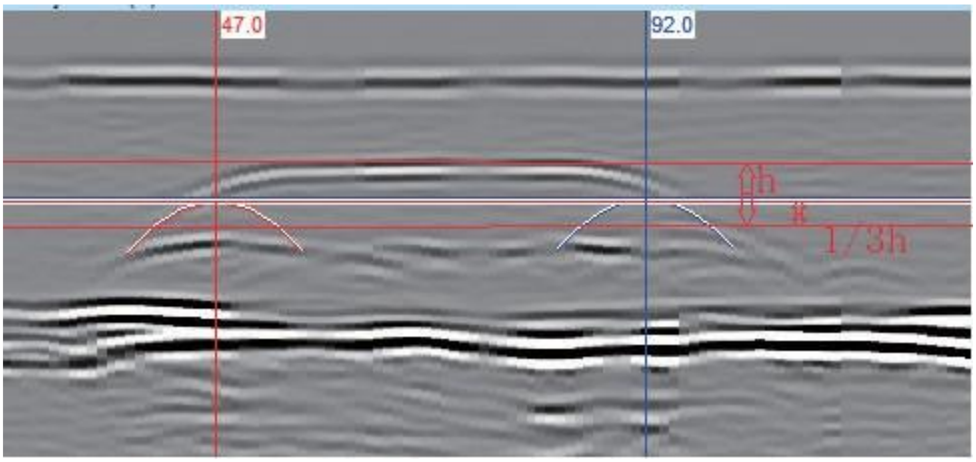


Figure A2.15 Length Measurement of Flaws with Relatively Long Arcs

A2.3.2 Depth and height measurement of flaws

In the measurement of the depth and height of flaws, there are three methods to determine the signal time, namely: the beginning point of signals, the first peak point and the highest peak point.

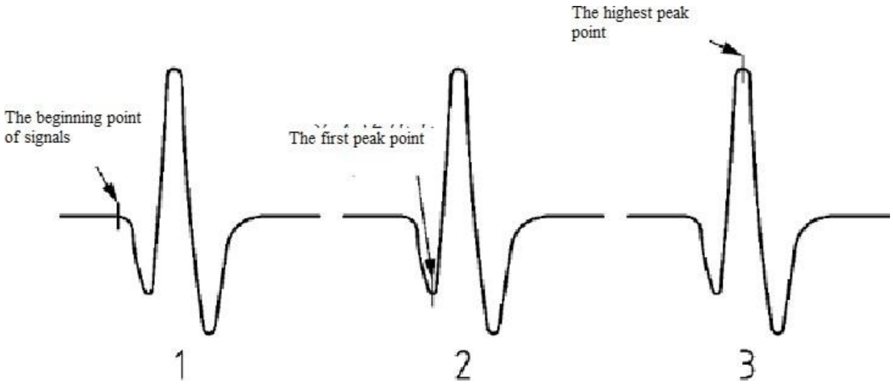


Figure A2.16 Methods to Measure the Signal Time

Under normal conditions, the phase of upper-tip diffraction signals of flaws is opposite to that of lateral waves but the same as back waves. The phase of the lower-tip diffraction signals is the same as lateral waves and opposite to that of back waves. The measurement of the depth and height of flaws is to refer to the phases of the corresponding signals.

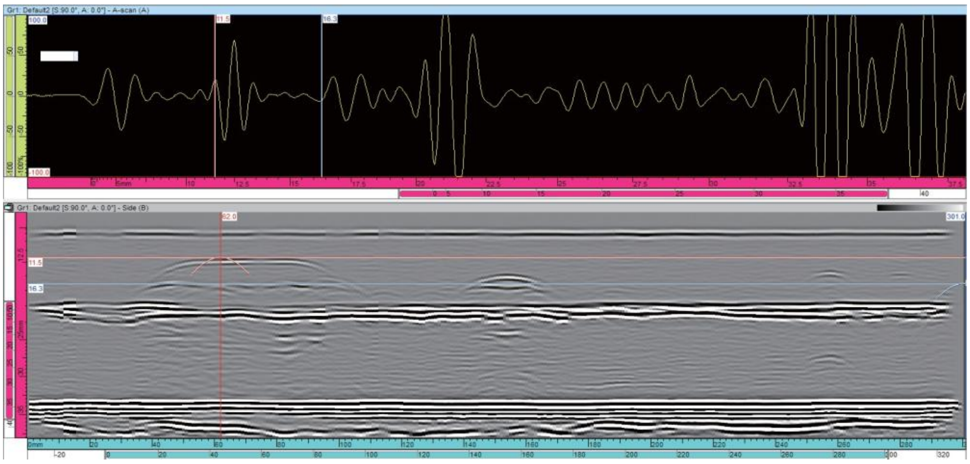


Figure A2.17 Methods for the Depth and Height Measurement of Flaws

The depth and height of flaws are defined as follows, in which h1 represents the depth of embedded flaws and h2 represents the height of flaws:

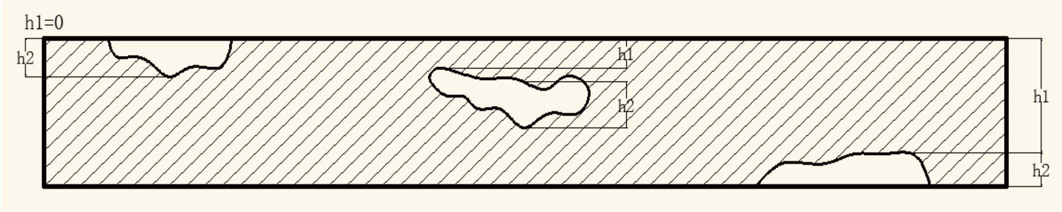


Figure A2.18 Definitions of the Depth and Height of Flaws

A2.3.3 Accurate sounding and horizontal positioning of flaws

The non-parallel scanning can be used to acquire the position of flaws of welds in the length-wise. But it cannot achieve the horizontal positioning of flaws. The use of parallel scanning can measure the depth and height of flaws and achieve the horizontal positioning. In parallel scanning, the real depth of the reflection point is displayed depth of the minimal point.

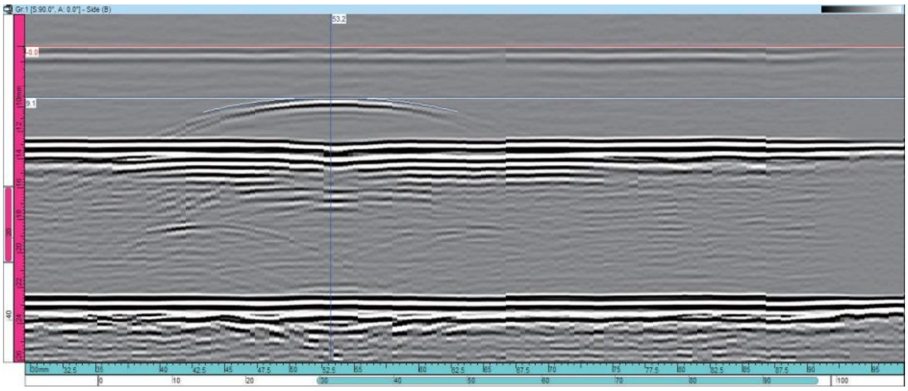


Figure A2.19 Image of Parallel Scanning and Measurement Method

Appendix 3 Blocks

A3.1 TOFD Reference Blocks

Typical TOFD reference blocks are shown in Figure A3.1 and the size of artificial reflector is shown in Tables A3.1, A3.2 and A3.3.

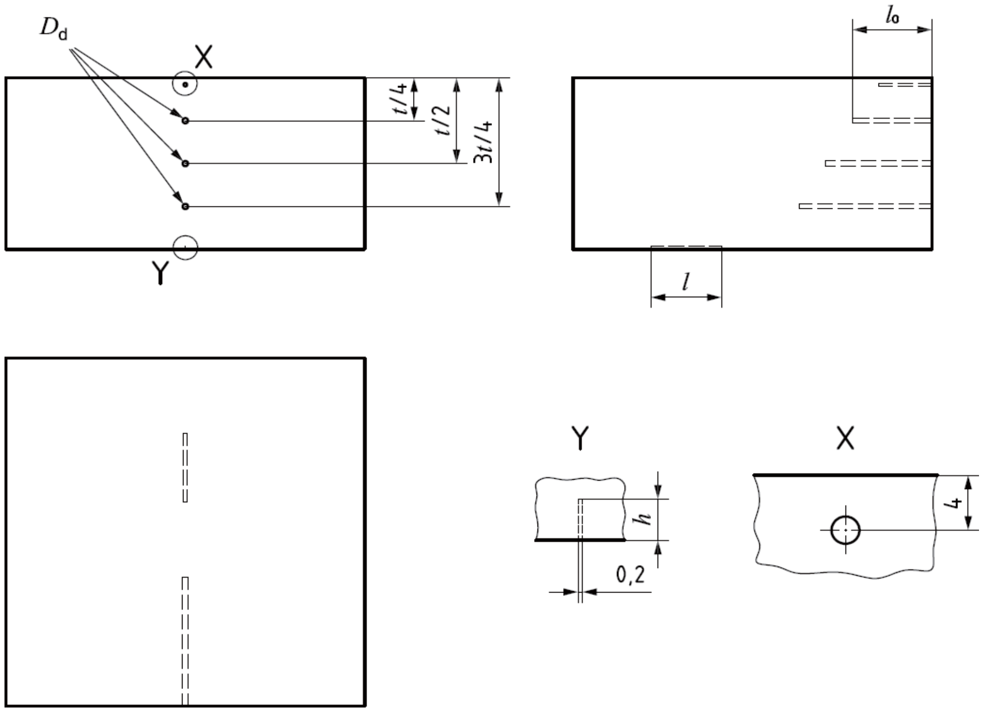


Figure A3.1 TOFD Reference Blocks

Sizes of the Bottom Notch-Groove of Reference Blocks   Table A3.1

Thickness of reference blocks *t*, mm	Length of the notch-groove *l*, mm	Depth of the notch-groove *h*, mm
$10 \le t \le 40$	*t*	1 ± 0.2
$40 < t \le 60$	40 ± 2	2 ± 0.2
$60 < t \le 100$	50 ± 2	2 ± 0.2
$t > 100$	60 ± 2	3 ± 0.2

Diameter of the Side Drilled Hole   Table A3.2

Thickness of reference blocks *t*, mm	Diameter of the side drilled hole D_d, mm
$10 \le t \le 25$	2.5 ± 0.2
$25 < t \le 50$	3.5 ± 0.2
$50 < t \le 100$	4.5 ± 0.2
$t > 100$	6.0 ± 0.2

Length of the Side Drilled Hole and Size of Surface Notch-Groove with the Thickness of the Plating Larger than 25mm Table A3.3

Thickness of reference blocks	Minimum length for 3 side drilled holes in one reference block , mm	Minimum length for one side drilled hole in 3 reference blocks, mm	Minimum length for 1 notch-groove in 3 reference block, mm
$t/4$	$l_0 = 45$	45	40
$t/2$	$l_0 + 15$	45	40
$3t/4$	$l_0 + 30$	45	40

A3.2 TOFD dead zone blocks

The standard reflector of dead zone blocks includes the side drilled hole and notch of back wall, among which the side drilled hole is 2 mm in diameter and the sharp-corner notch is 3 mm in breadth. The depth and position of artificial flaws are shown in Figure A3.2.

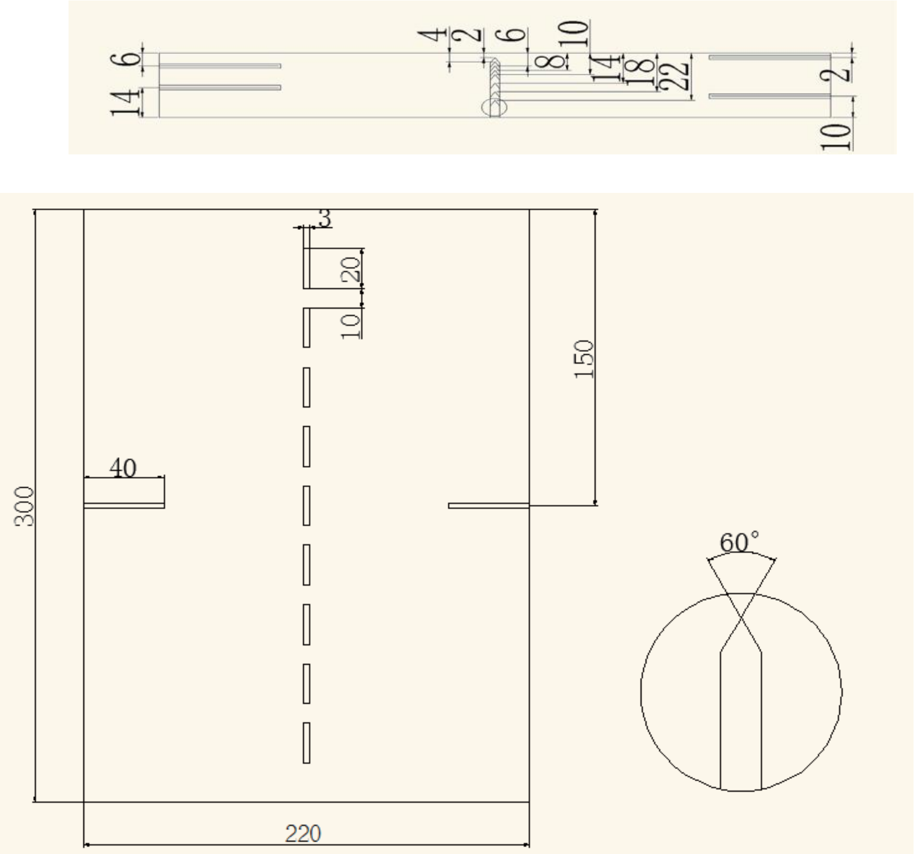
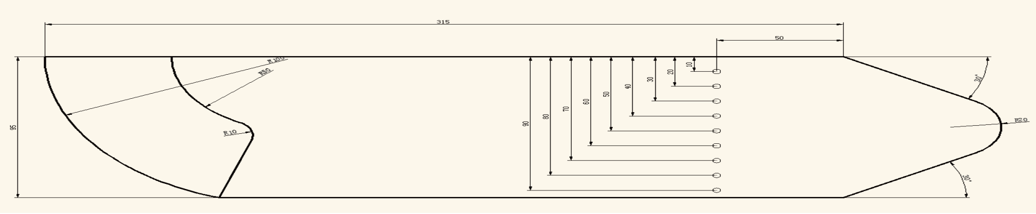


Figure A3.2 TOFD Dead Zone Blocks

A3.4 PAUT reference blocks



Requirements for manufacturing:

1. Diameter of the side drilled hole is 3 mm, the error of which is required to be less than 0.2 mm.

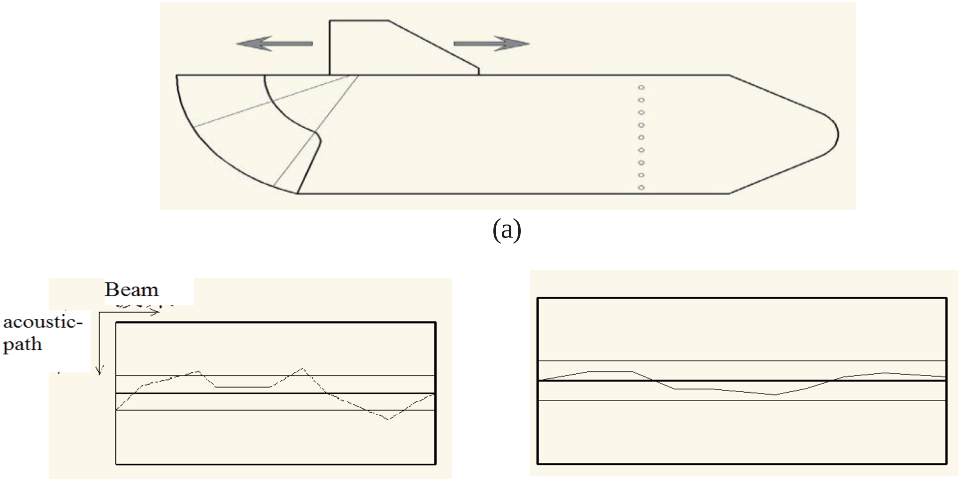
2. The error of each size is not to be greater than 0.2 mm.

3. The angle error is not to be greater than 2 degrees.

Appendix 4 Methods of Equipment Calibration

A4.1 Wedge delay calibration

The wedge delay calibration is to adopt the R100 arc of reference blocks as shown in Figure A4.1 (a). In calibration, the instrument is adjusted to the acoustic-path display mode. The probes are moved back and forth so that beams in each angle can gain the transit time of the highest wave signals of arcs. Records will be done by the instrument as shown in Figure A4.1 (b). Use the calibration function to adjust the time delay of each beam so that each half acoustic-path R100 arc is 100 mm. After calibration, the probes will be moved back and forth again in the same position to see whether the errors of wedge delay after calibration are within the required error band as shown in Figure A4.1(c).



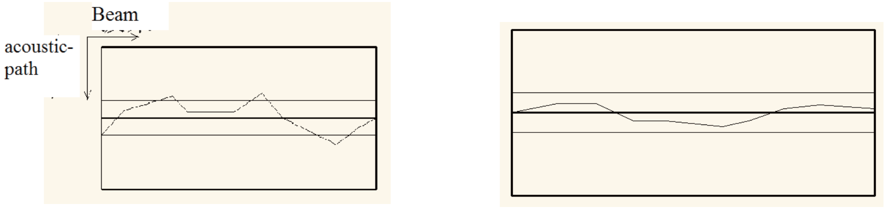
(a)

(b) (c)

Figure A4.1 Wedge Delay Calibration

A4.2 Angle Corrected Gain (ACG)

ACG is to adopt the R100 arc in reference blocks as shown in Figure A4.1 (a). In calibration, the instrument is adjusted to the acoustic-path display mode. The probes are moved back and forth so that beams in each angle can gain the amplitude of the highest wave signals of arcs. Records will be done by the instrument. Use the calibration function to adjust the gain of each beam so that the reflection echo height of each beam on the R100mm arc surface is the benchmark wave height. After calibration, the probes will be moved back and forth again in the same position to see whether the errors of amplitude after calibration are within the required error band.

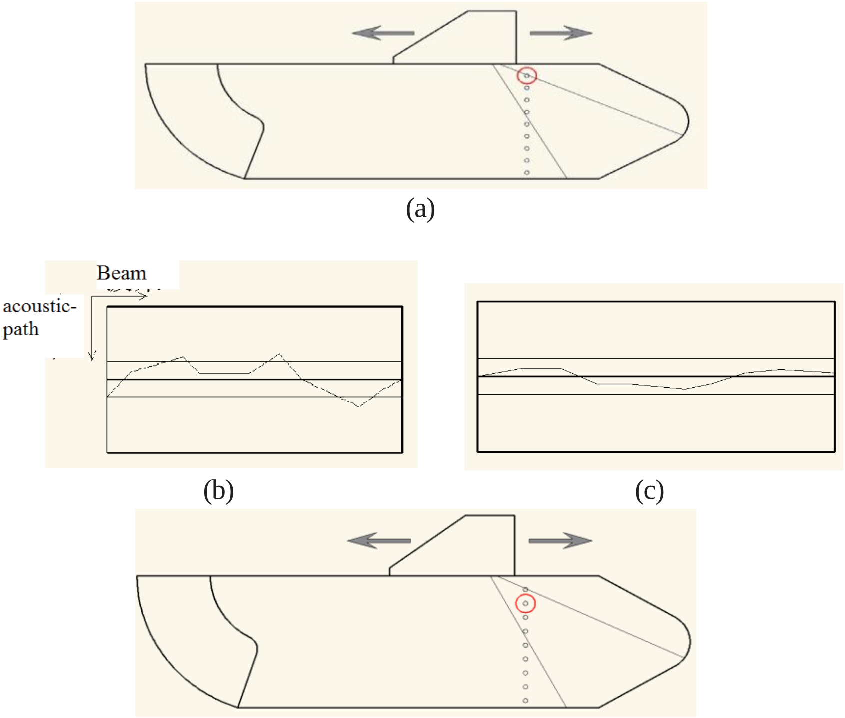


(a) (b)

Figure A4.2 ACG Calibration

A4.3 TCG Calibration

TCG calibration adopts side drilled holes of different depths on reference blocks as shown in Figure A4.3 (a). In calibration, the instrument is adjusted to the depth display mode. The probes are moved back and forth so that beams in different angles can all collect the highest echo of side drilled holes at a certain depth. Each echo height will be recorded by the instrument as shown in Figure A4.3 (b). Use the calibration function to adjust the gain of each beam so that the reflection echo height of different beams against the same side drilled hole all reaches the benchmark echo height. After calibration, the probes will be moved again in the same position to see whether the results after calibration meet the error requirements of calibration as shown in Figure A4.3 (c).



(a)

(b) (c)

(d)

Figure A4.3 TCG Calibration

Repeat the above steps to calibrate the next side drilled hole as shown in Figure A4.3 (d) until the calibrated depth covers the testing depth.

A4.4 Encoder Calibration

In the calibration of an encoder, the encoder is to be moved by a certain distance (no less than 500 mm). After the input of the moving distance, the instrument will calculate the resolution ratio automatically based on the pulse counts received to complete the calibration.

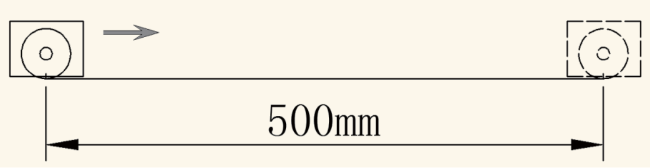


Figure A4.4 Encoder Calibration

Appendix 5 The Effect of Probe Excitation Aperture and Depth of Focus on Imaging Results of S-Scan

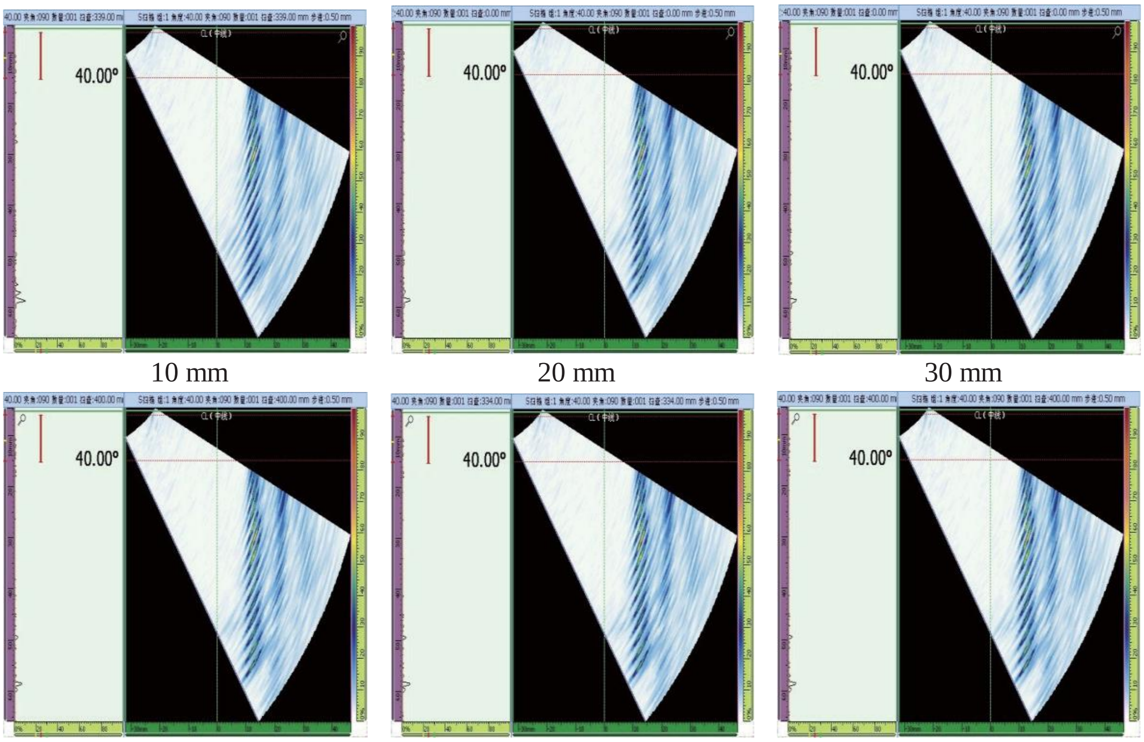
A5.1

Probe: 5MHz probe, element pitch is 0.6 mm and the breadth is 10 mm;

Wedge: 55 degrees of transverse wave wedge

Focal law: excite 16 Elements out of 32, 40～70 degrees of transverse wave S-Scan, depth of focus is from 10 to 60 mm.

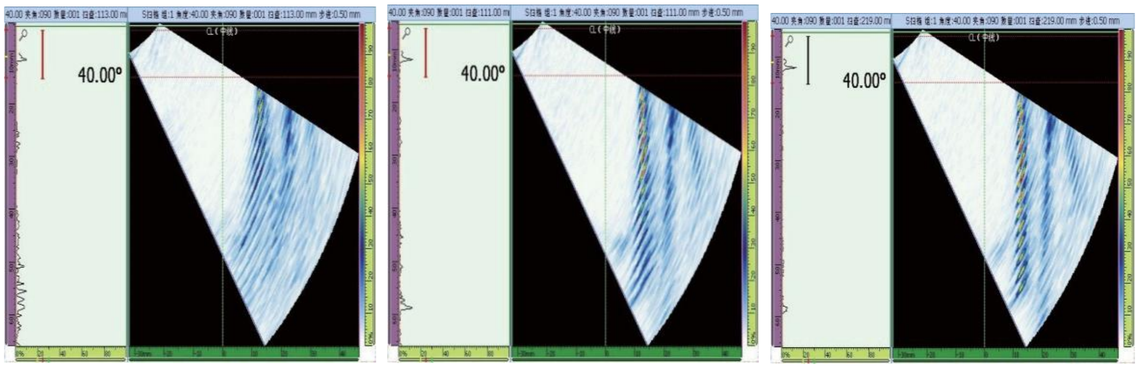
Artificial reflector: Long side drilled hole, from 20 to 55 mm in depth



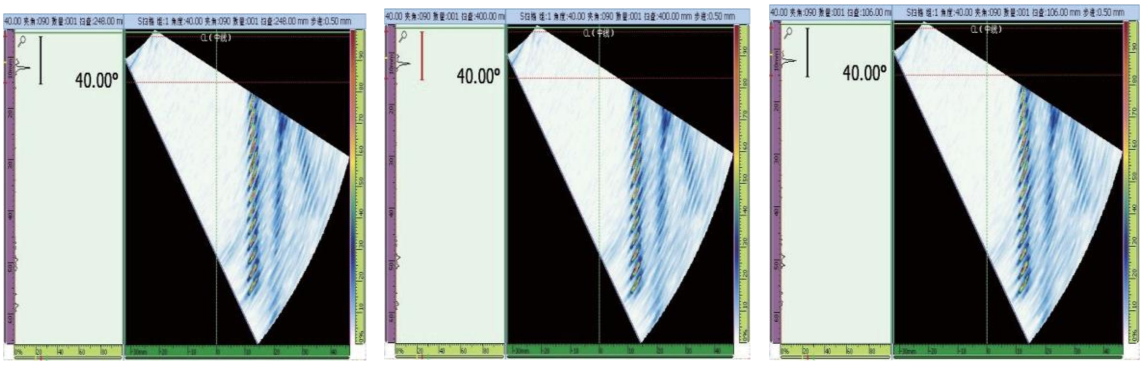
10 mm 20 mm 30 mm

40 mm 50 mm 60 mm

Figure A5.1 Focus Imaging Results of S-Scan by Exciting 16 Elements



10 mm 20 mm 30 mm



40 mm 50 mm 60 mm

Figure A5.2 Focus Imaging Results of S-Scan by Exciting 32 Elements

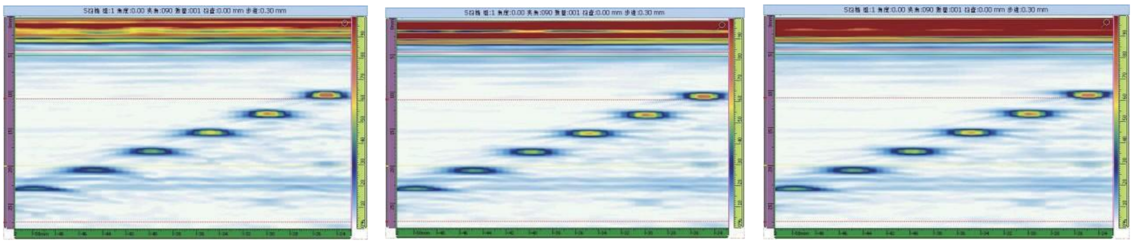
A5.2

Probe: 5MHz probe, element pitch is 0.6 mm and the breadth is 10 mm;

Wedge: 0 degree of delay wedge

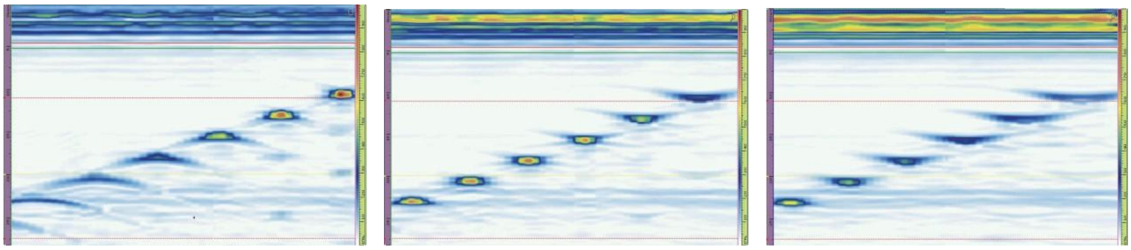
Focal law: excite 16 Elements out of 32, 0 degree of longitudinal wave E-Scan, depth of focus is from 10 to 60 mm.

Artificial reflector: Long side drilled hole, from 20 to 55 mm in depth.



10 mm 20 mm 30 mm

Figure A5.3 Focus Imaging Results of E-Scan by Exciting 16 Elements



10mm 20mm 30mm

Figure A5.4 Focus Imaging Results of E-Scan by Exciting 32 Elements

Appendix 6 Typical Images of Flaws

A6.1 Lack of fusion of grooves

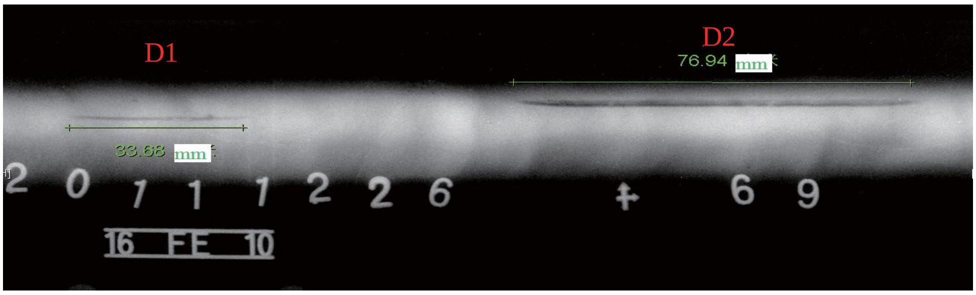


Figure A6.1(a) Butt Weld of Plates

(Plate thickness: 20 mm, single V groove, manual CO_2
gas shielded welding, breadth of weld reinforcement: 33 mm)

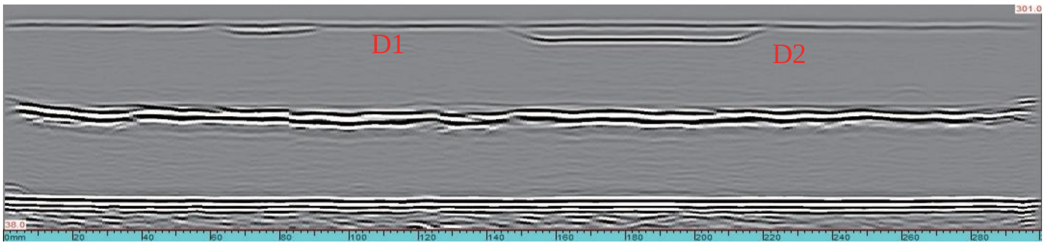


Figure A6.1(b) Testing Results of TOFD Testing B-Scan (5MHz, Φ6mm probe)

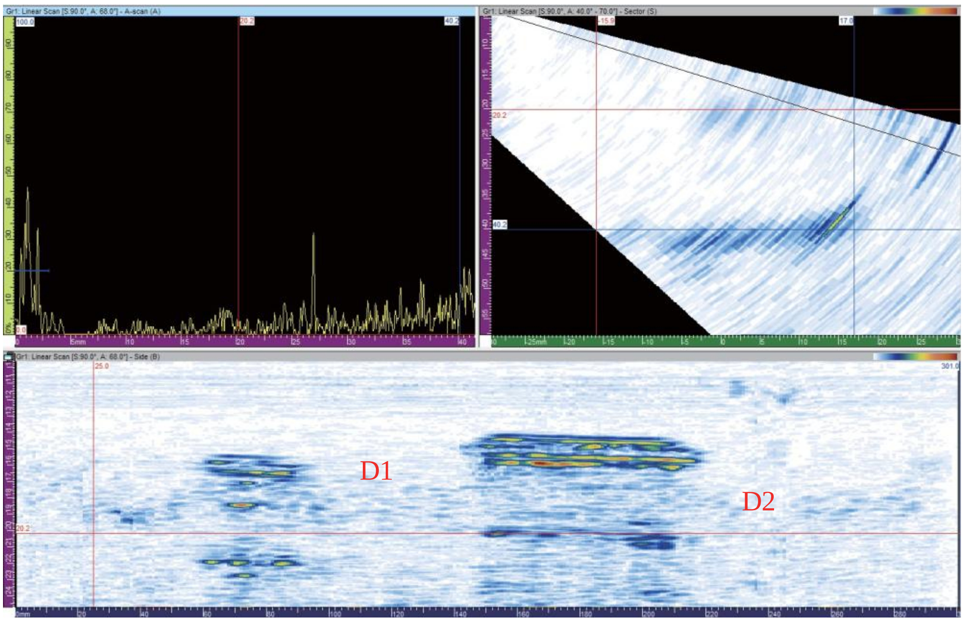


Figure A6.1(c) S-Scan Image of Flaw-Free Positions

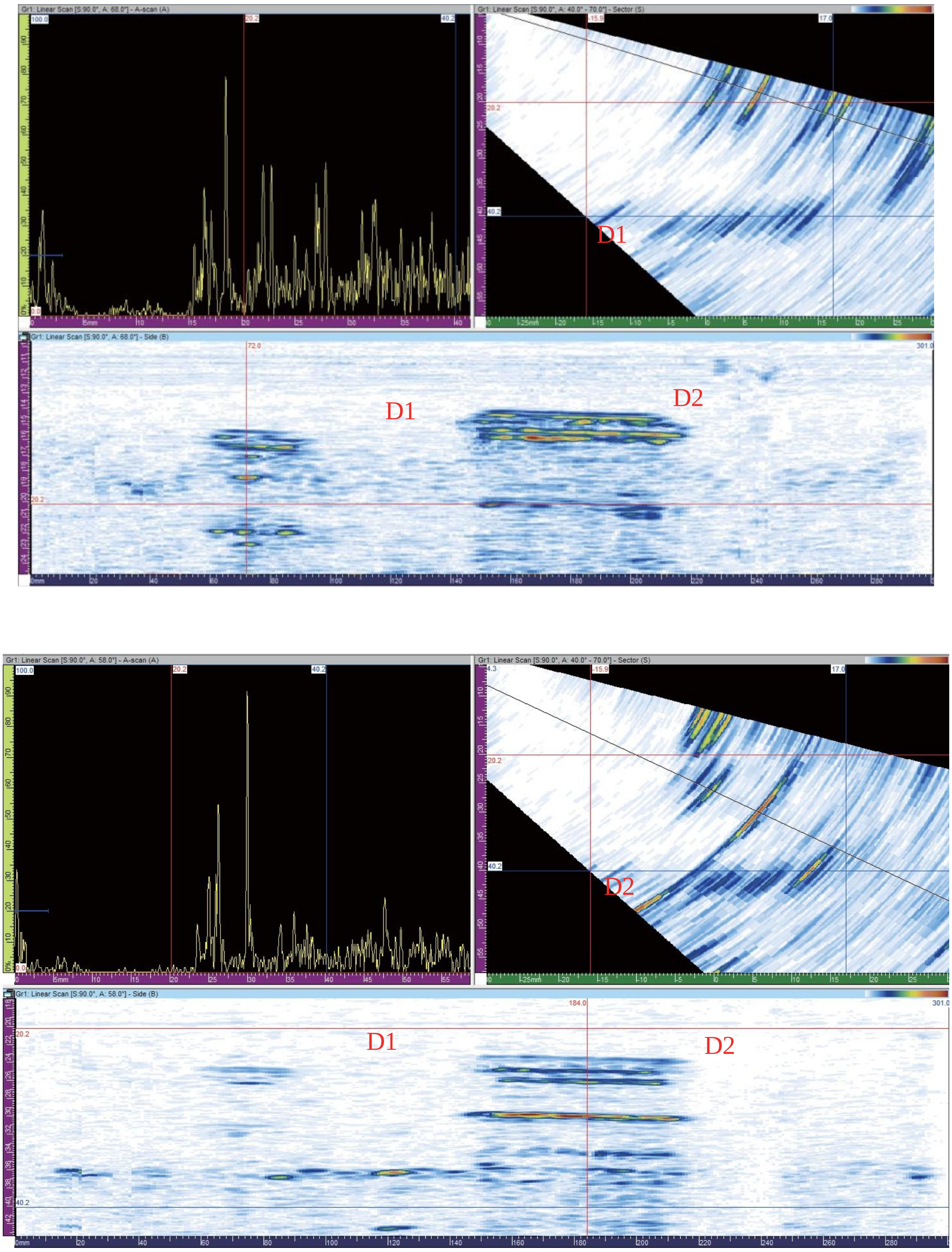


Figure A6.1(d) PAUT Testing Results

(5MHz, 16-Element probe, 0.6 mm*10 mm, 55 degrees of transverse wave wedge, S-Scan: 40°~70°)

A6.2 Strip-like slag inclusion

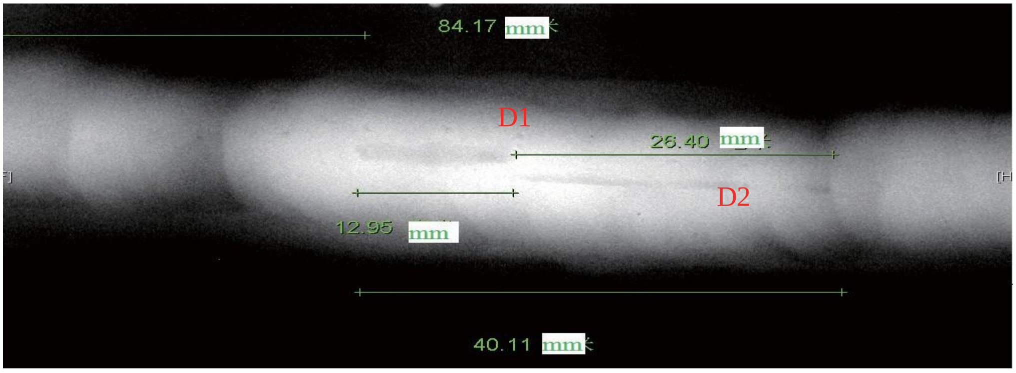


Figure A6.2(a) Butt Weld of Plates

(Plate thickness: 18 mm, single V groove, manual CO_2 gas shielded welding,
breadth of weld reinforcement: 35 mm)

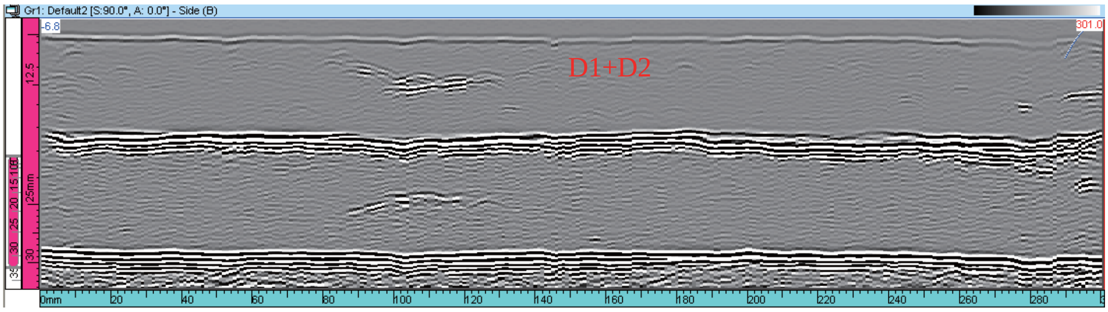


Figure A6.2(b) Testing Results of TOFD Testing B-Scan (10MHz, Φ3mm probe)

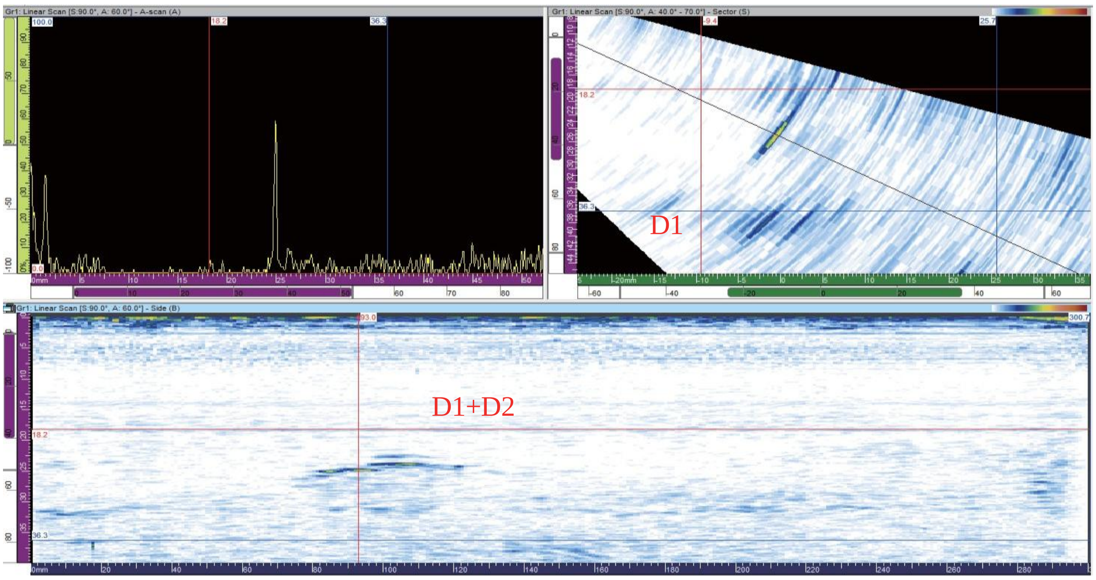


Figure A6.2(c) PAUT Testing Results

(5MHz, 16-Element probe, 0.6 mm*10 mm, 55 degrees of transverse wave wedge, S-Scan: 40°~70°)

A6.3 Pores (single pores, cluster pores, scattered pores)

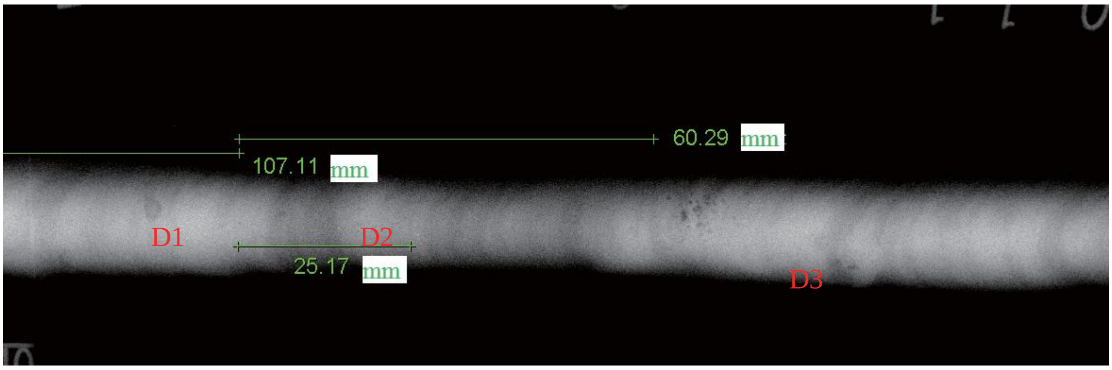


Figure A6.3(a) Butt Weld of Plates

(Plate thickness: 20 mm, single V groove, manual CO_2 gas shielded welding,
breadth of weld reinforcement: 35 mm)

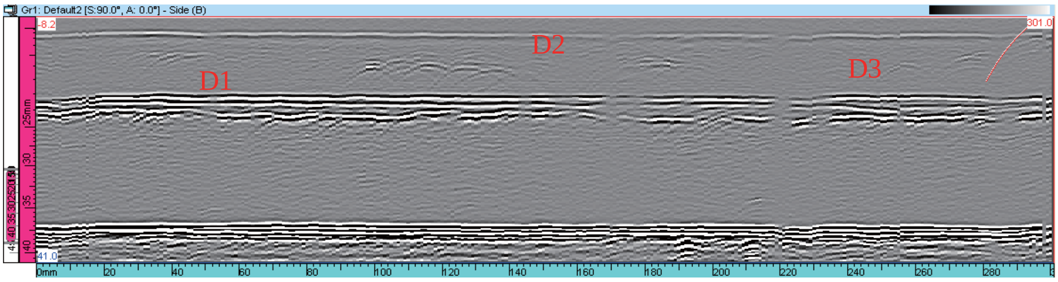
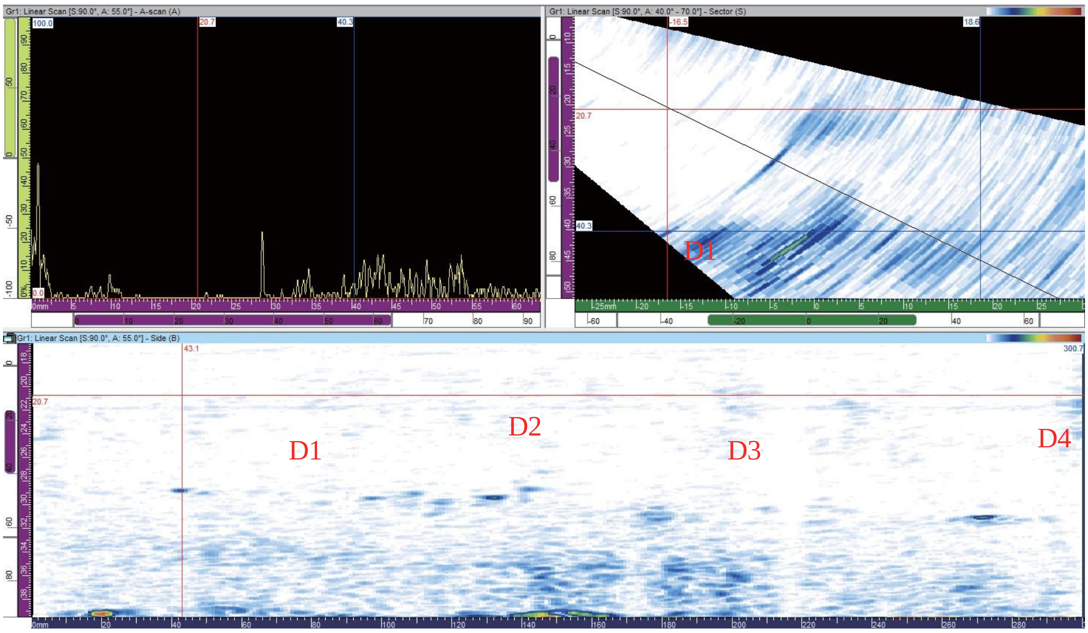
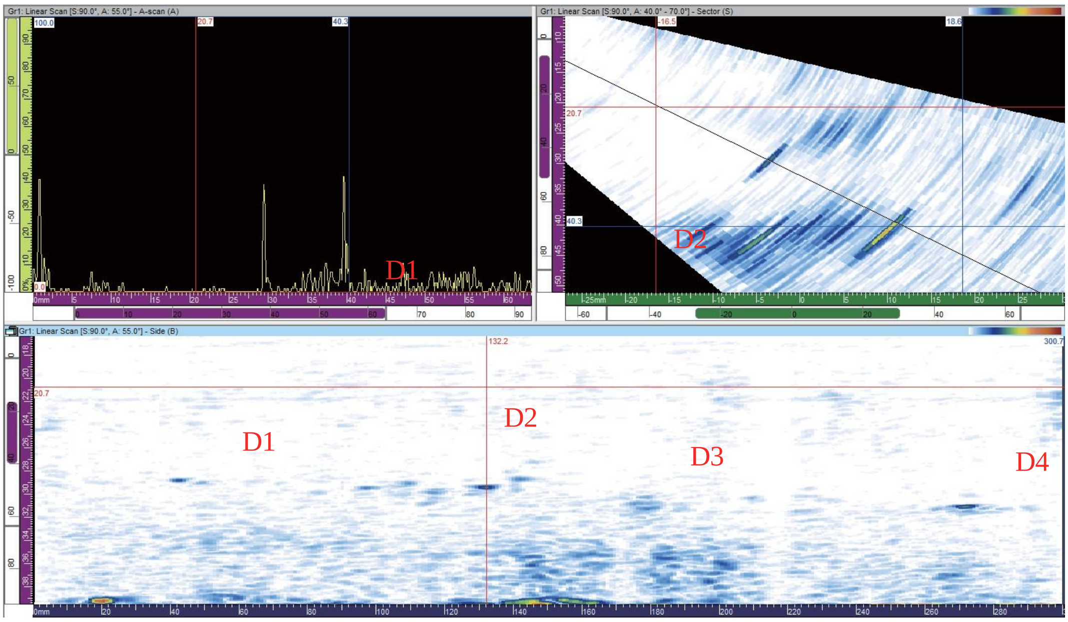


Figure A6.3(b) Testing Results of TOFD Testing B-Scan (10MHz, Φ3mm probe)


Gr1: Linear Scan [S:90.0°, A: 55.0°] - A-scan (A)
Gr1: Linear Scan [S:90.0°, A: 40.0° - 70.0°] - Sector (S)
20.7
40.3
-16.5
18.6
D1
Gr1: Linear Scan [S:90.0°, A: 55.0°] - Side (B)
43.1
300.7
D1
D2
D3
D4


Gr1: Linear Scan [S:90.0°, A: 55.0°] - A-scan (A)
Gr1: Linear Scan [S:90.0°, A: 40.0° - 70.0°] - Sector (S)
20.7
40.3
-16.5
18.6
D1
D2
Gr1: Linear Scan [S:90.0°, A: 55.0°] - Side (B)
132.2
300.7
D1
D2
D3
D4

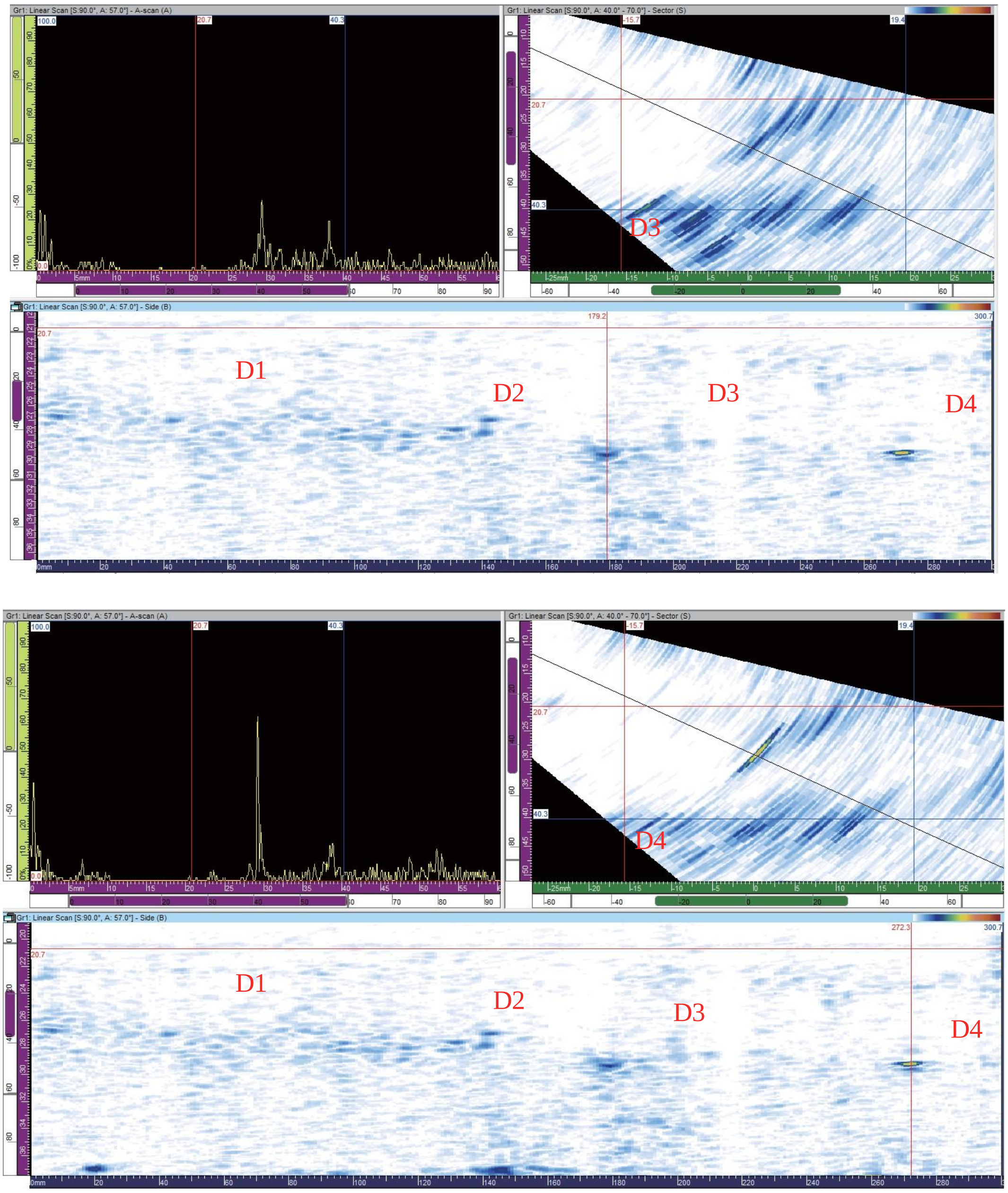


Figure A6.3(c) PAUT Testing Results

(5MHz, 16-Element probe, 0.6 mm*10 mm, 55 degrees of transverse wave wedge, S-Scan: 40°~70°)

A6.4 Cluster pores, incomplete penetration

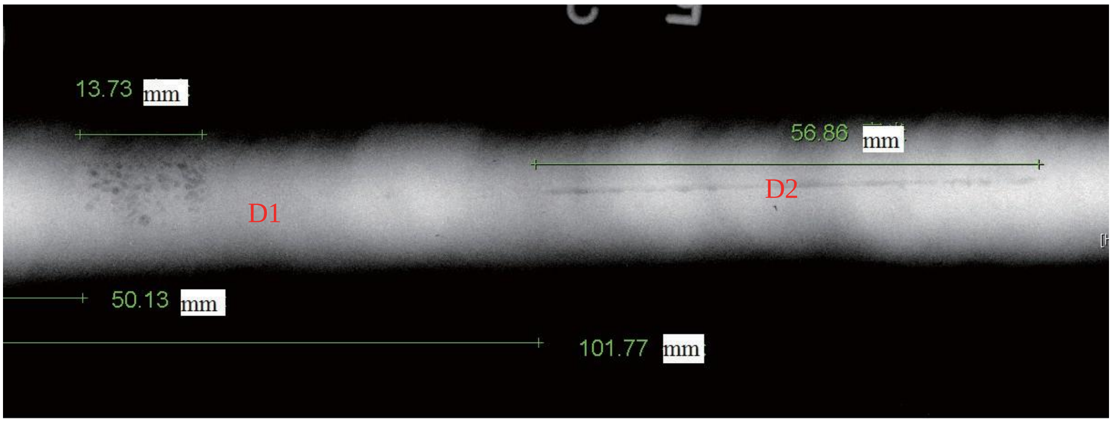


Figure A6.4(a) Butt Weld of Plates

(Plate thickness: 20 mm, single V groove, manual CO_2 gas shielded welding, breadth of weld reinforcement: 30 mm)

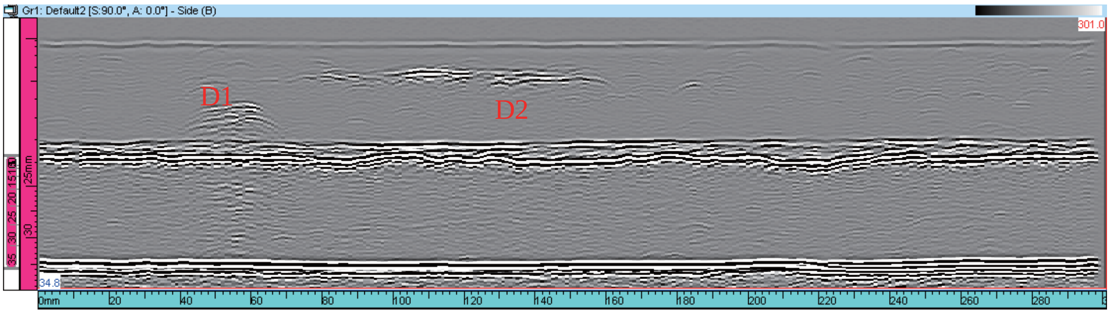


Figure A6.4(b) Testing Results of TOFD Testing B-Scan (10MHz, Φ3mm probe)

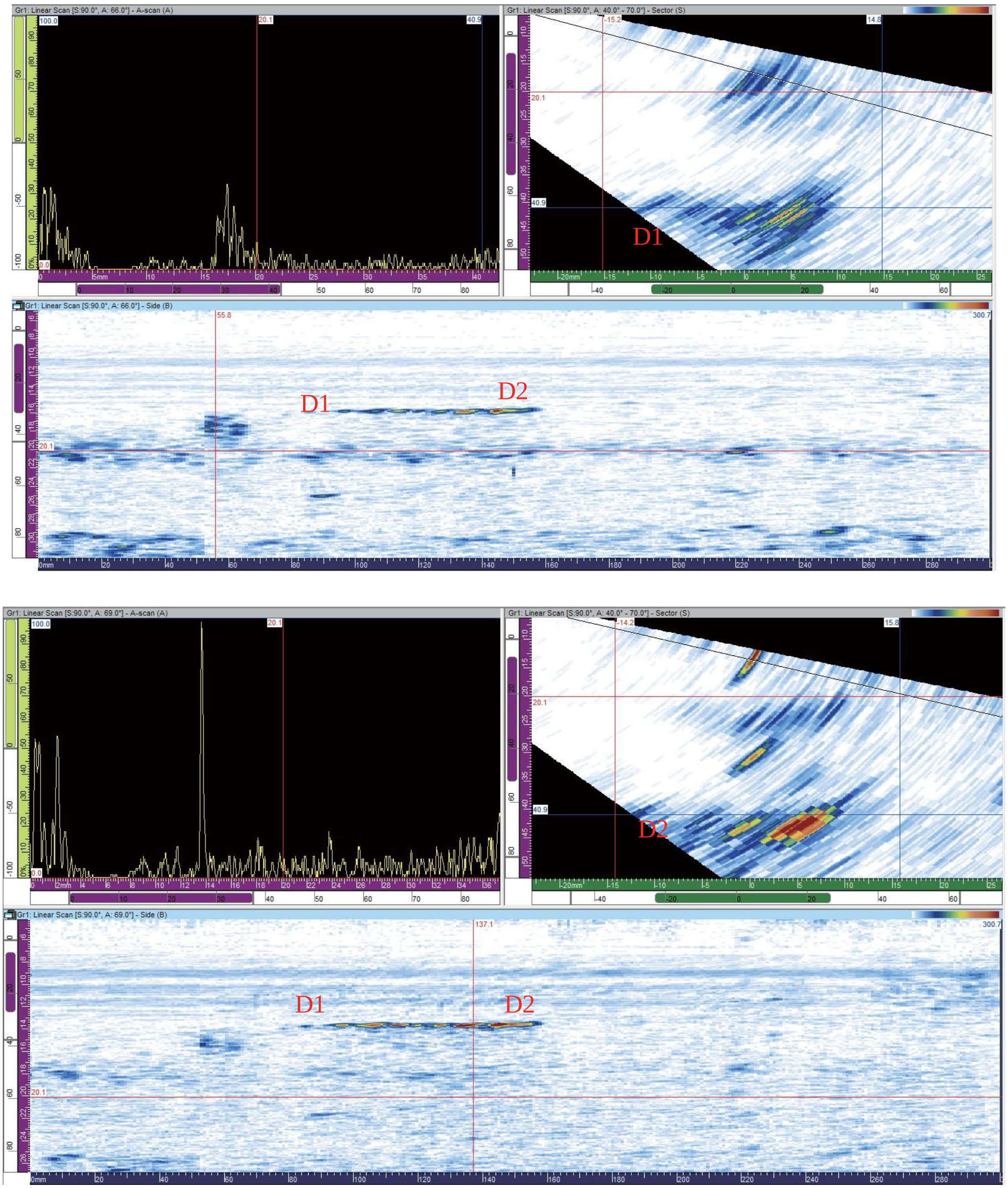


Figure A6.4(c) PAUT Testing Results

(5MHz, 16-Element probe, 0.6 mm*10 mm, 55 degrees of transverse wave wedge, S-Scan: 40°~70°)