DNT INSPECTION SERVICE CO., LTD.

TIME OF FLIGHT DIFFRACTION (TOFD) PRINCIPLES

TOFD is now becoming a standard technique for both power generation and petrochemical industries. TOFD can also be performed by phased array probes; TOFD is simply a procedure that uses two probes in pitch-and-catch mode. The main difference between power generation and petrochemical applications is that power generation applications typically use raster TOFD, while the petrochemical industry and other industries use linear TOFD. Raster TOFD collects more data and is more accurate, while linear TOFD is faster. Most of the weld caps in power generation are removed, which permits raster scanning.

> **Note:** *Linear scanning* is single-axis scanning parallel to the weld. *Raster scanning* is an *x-y* back-and-forth scanning motion.

TOFD detects and records signals diffracted from defect tips for both detection and sizing. The TOFD data is displayed in a gray-scale B-scan. Modifications to this standard setup are possible.

Four types of waves are used in TOFD:

- The *lateral wave*: A sub-near-surface longitudinal wave generated from the wide beam of the probe.
- The *backwall reflection*: A longitudinal wave reflected from the backwall.
- The *reflected wave*: A longitudinal wave reflected by a lamellar planar defect.
- The *tip diffracted wave*: A circular wave diffracted by the edge of a defect. Both longitudinal and shear waves are normally generated, but L-waves are typically used for TOFD.

The TOFD method is based on the following principles:

- Pitch-and-catch setups are in LW configuration (see Figure 2-40).
- The probes are high-damped (1.5 λ, or white-black-white, with $BW_{rel} > 90\%$) and high-frequencied (>6 MHz).
- The beam divergence is large enough to produce lateral waves and a backwall reflection, so the entire wall thickness is displayed between the lateral waves and backwall (skipped) signals.
- The probes are typically centered over the weld center line.
- For walls thicker than 75 mm, double TOFD pairs should be used.
- Wedge delay, velocity in the test piece, lateral wave TOF, backwall TOF value, thickness, and PCS (probe center separation) must be known (though some can be deduced).
- Upper-tip and lower-tip echoes have phase reversal (see Figure 2-40 for an illustration of the physics).
- Additional defect image recognition can be performed with mode-converted (LT, TL) signals.
- A preamplifier is often required to display the digital signals from defect edges, which are −20 dB to −30 dB lower than a 3 mm side-drilled hole signal at the same range.
- Maximum amplitudes of diffracted signals are obtained at about 70°.
- L-waves are preferred to T-waves for their "first-hit" arrival at the defect edges; they are also less attenuated by test piece structure.
- Linear scanning is performed in a single scan, parallel with the weld center line.

Assuming the defect is symmetrically placed between probes, the following formulas are used to measure defect height h ($2a$) and the upper ligament (d):

$$T_{\text{lat. wave}} = \frac{PCS}{v_L} = \frac{2S}{v_L} \quad (2.41)$$

$$T_{\text{upper tip}} = \frac{2(S^2 + d^2)^{0.5}}{v_L} \quad (2.42)$$

$$T_{\text{lower tip}} = \frac{2[S^2 + (d+h)^2]^{0.5}}{v_L} \quad (2.43)$$

$$T_{\text{backwall}} = 2(S^2 + t^2)^{0.5} \quad (2.44)$$

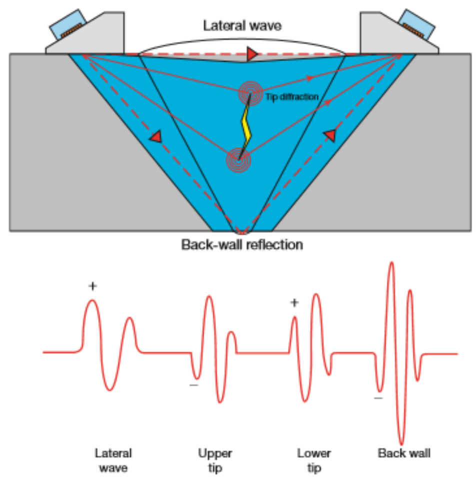


Figure 2-40 Principle of TOFD and the phase sign of four major signals. The defect is assumed to be symmetrically located between the probes. The phase of each RF signal is marked with "+" and "–".

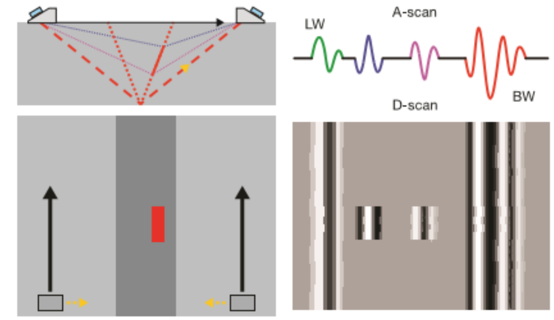


Figure 2-41 Detection and sizing of a lack of fusion by TOFD D-scan. Phase reversal of upper and lower defect edges is displayed in gray levels.

TOFD limitations

- Defects located at upper surface and inner surface are difficult to detect due to the dead zone of the lateral wave and because of the dead zone of the backwall signal (see Figure 2-42).

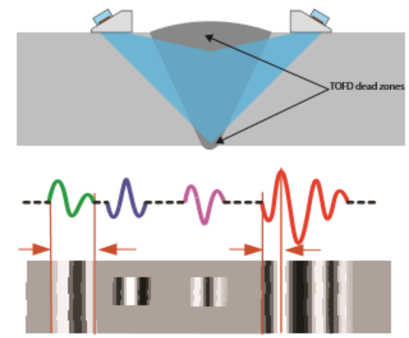


Figure 2-42 TOFD dead zones due to lateral waves and backwall. Dead zone size depends on frequency, pulse length, probe center separation, material thickness, and velocity. Errors can occur with TOFD if the defect is not symmetrically placed between the two probes.

- Defect location in a linear D-scan has some errors due to TOF locus (see Figure 2-43), since time of arrival of diffracted waves depend on defect position relative to the probes. The location of the defect is estimated by an additional B-scan over the defect position (when probes are moving transverse to the weld).
- Defect interpretation and defect pattern recognition require advanced training and analysis experience.
- Pressure vessel with shells thickness greater than 75 mm require multipass scanning with different PCS.
- Low signal-to-noise ratio.
- Signals sensitive to coarse-grained material.
- Geometry and coupling problems may hamper the propagation of the lateral wave.
- Amplitude is not related to defect size or importance.

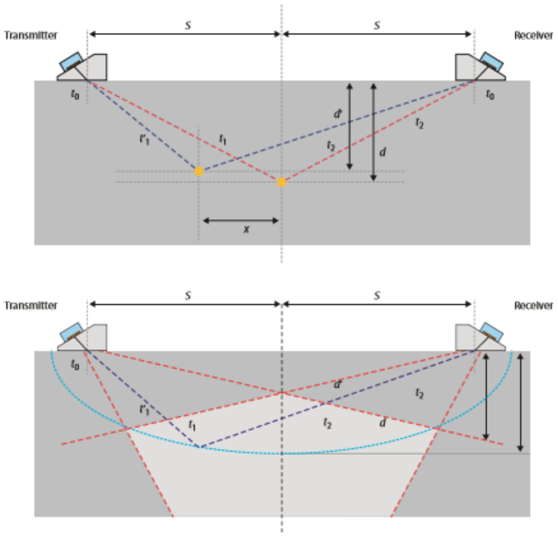
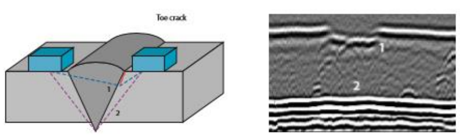


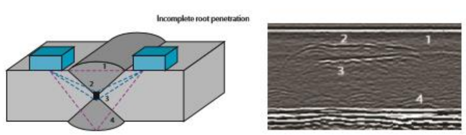
Figure 2-43 TOFD errors in lateral location and upper ligament caused by the TOF locus of L-waves.

In spite of these limitations, TOFD is *the most accurate* UT technique for crack sizing (both length and specifically height). TOFD was accepted as an alternative to assess the weld quality of pressure vessels in ASME Code Case 2235.

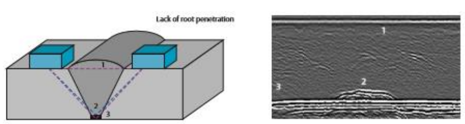
For improved reliability of defect detection, Olympus has proposed a combination of TOFD and pulse-echo, so a real-time display with image recognition is available on a specific layout. Figure 2-44 (a) to Figure 2-44 (h) show typical defects and their corresponding TOFD displays.



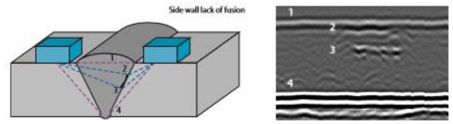
(a) For the toe crack, the lateral wave is disrupted and the bottom of the crack visible. This can be characterized as a surface-breaking crack, and depth measured.



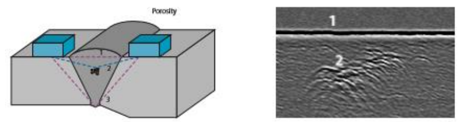
(b) For the incomplete root penetration, the top and bottom diffracted signals are distinguishable, while the uninterrupted lateral and backwall signals indicate a buried defect.



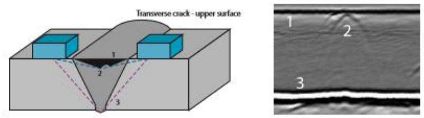
(c) For the lack of root penetration, the backwall is perturbed but not broken, while the top diffracted signal is visible. This indicates a surface-breaking defect.



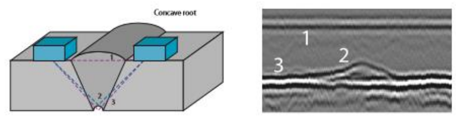
(d) The lack of sidewall fusion shows no lateral or backwall perturbation, so shows a buried defect. The bottom diffracted signal is clear, but the top diffracted signal is partly buried in the lateral wave.



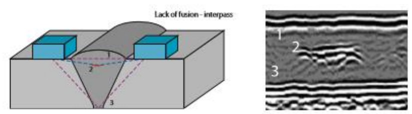
(e) The porosity shows as a series of point defects with associated hyperbolic tails. Multiple porosity is difficult to analyze, but easily characterized. Note that the backwall signal is not displayed in this TOFD image.



(f) The transverse defect shows essentially as a point defect, similar to porosity.



(g) The concave root defect perturbs the backwall signal (showing it is surface breaking), while the tip is visible.



(h) The interpass lack of fusion shows as a single reflected signal of high amplitude, but would not be detectable on the pulse-echo channels.

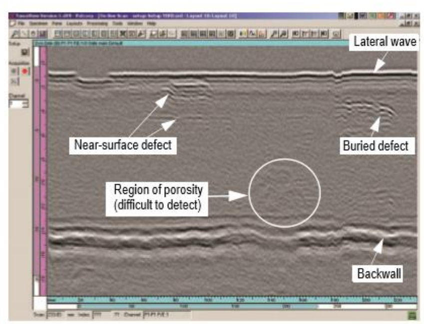


Figure 2-44 TOFD imaging of defects in weld.

Benefits

- Single pass
- Real-time A-scans, B-scans, and C-scans
- High-accuracy sizing: TOFD
- High SNR: focused-beam phased array ultrasounds
- High accuracy in defect positioning
- Easy reporting

PAUT combine TOFD